An Evaluation of Short-Term Exposures to Metalworking Fluids in Small Machine Shops

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In a study of 23 small machining shops using metalworking fluids (MWFs), real-time air monitoring using an aerosol photometer was performed to investigate the temporal nature of the exposure and to examine the relationship between the instrumental measurements and traditional sampling methods. Time-weighted averages were calculated from the aerosol photometer data and the results were compared to collocated thoracic and 37-mm closed face cassette samplers. The filter samples were analyzed for total mass and the solvent extractable fraction. Depending on the averaging period used, short-term MWF concentrations exceeded 2.0 mg/m³ in 13 to 39% of the plants studied. High short-term exposures were as likely to be found in plants with average concentrations below 0.4 mg/m³ (thoracic-gravimetric) as those above. Regression analyses indicated that the aerosol photometer most closely matched the data obtained from the thoracic fraction of the total mass. In general, the aerosol photometer overestimated the levels determined using the thoracic cyclone and filter, especially when measuring concentrations of water-based fluids. Use of a calibration factor of 0.7 for straight oils or 0.5 for water-based fluids may assist in the interpretation of aerosol photometer measurements if field calibration data are not readily available. Several approaches to determining the calibration factor from field data were evaluated; more complex calibration techniques improved the accuracy of the measurements.
Keywords: machining shops, metalworking fluids

Metalworking fluid (MWF) is a generic term used to cover machining fluids and cutting oils used for cooling, flushing, and lubricating machine tools and metal parts during machining operations such as drilling, grinding, turning, and milling. MWFs are generally grouped into four major categories: straight (undiluted mineral/fatty oils); soluble (water emulsions of mineral/fatty oils); synthetic (chemical solutions of organic compounds in water); and semisynthetic (emulsions of mineral oil with water and organic compounds similar to those found in synthetics). An estimated[1] 1.2 million workers in the United States are potentially exposed to MWFs. Occupational exposures to MWFs may be affected by several factors, such as fluid type; machining operation, including tool type and speed; fluid application method; engineering controls, including machine enclosures and local exhaust ventilation systems; and fluid and machine maintenance.

The National Institute for Occupational Safety and Health[1] (NIOSH) has published criteria recommending that exposure to MWFs be limited to 0.4 mg/m³ on a full-shift basis as thoracic mass. This recommendation was made to minimize the risk of respiratory effects. The possibility exists that short-term peak exposures are important determinants of some of the respiratory disorders induced by MWF aerosols. Some[2,3] have proposed that either a short-term exposure limit or a ceiling limit of 2.0 mg/m³ may be more protective of worker health and safety, or that such a limit should at least be coupled with a time-weighted average exposure limit. In general, the American Conference of Governmental Industrial Hygienists[4] (ACGIH) recommends that "excursions in worker exposure levels may exceed 3 times the TLV-TWA [threshold limit value, time-weighted average] for no more than a total of 30 minutes during the workday, and

TABLE I. Airborne Concentration of MWF in 23 Plants

Fluid	MWF Aerosol Concentration (mg/m³)							
	Aerosol Photometer				Thoracic Cyclone		Closed-Face Cassette	
	Peak Instant.	Peak 1 m	Peak 15 m	TWA 8 hr	Gravimetric	Extractable	Gravimetric	Extractable
Semisynthetic	2.35	0.64	0.28	0.19	0.11	0.08	0.16	0.10
Semisynthetic	21.3	7.97	7.24	0.51	0.30	0.20	0.40	0.25
Semisynthetic	5.73	3.30	1.48	1.02	0.39	0.36	0.43	0.41
Synthetic	0.96	0.74	0.39	0.15	0.13	0.07	0.18	0.12
Synthetic	2.31	1.43	0.45	0.18	0.21	0.10	0.64	0.46
Synthetic	15.0	3.45	1.44	0.93	0.40	0.35	0.49	0.43
Soluble oil	0.45	0.14	0.06	0.04	0.04	0.01	0.03	0.01
Soluble oil	0.28	0.51	0.17	0.09	0.10	0.05	0.15	0.09
Soluble oil	0.92	0.52	0.30	0.13	0.13	0.05	0.19	0.12
Soluble oil	1.30	0.59	0.48	0.34	0.27	0.23	0.28	0.26
Straight oil	0.87	0.41	0.20	0.10	0.13	0.11	0.16	0.16
Straight oil	0.59	0.31	0.28	0.11	0.16	0.14	0.14	0.15
Straight oil	3.30	1.00	0.60	0.36	0.20	0.16	0.28	0.24
Straight oil	1.39	1.31	1.13	0.68	0.29	0.23	0.38	0.24
Straight oil	1.95	1.53	1.25	0.38	0.30	0.27	0.48	0.47
Straight oil	1.75	1.09	0.86	0.40	0.33	0.29	0.66	0.62
Straight oil	1.47	0.80	0.74	0.38	0.37	0.30	0.61	0.54
Straight oil	17.1	5.68	3.94	0.90	0.39	0.35	0.43	0.38
Straight oil	11.2	2.86	1.86	1.25	0.62	0.51	0.84	0.61
Straight oil	2.55	2.55	0.98	0.62	0.65	0.57	1.25	1.11
Straight oil	17.7	5.97	2.14	1.23	1.03	0.91	1.32	1.13
Straight oil	4.85	4.53	3.51	1.82	1.09	0.96	1.19	1.12
Straight oil	3.11	1.72	1.30	0.90	1.15	1.11	1.36	1.30

under no circumstances should they exceed 5 times the TLV-TWA, provided that the TLV-TWA is not exceeded." When applied to the NIOSH recommended exposure limit (REL), the ACGIH recommendation would be equivalent to a ceiling limit for MWF aerosol of 2.0 mg/m³.

One difficulty in adopting either a short-term exposure limit or a ceiling limit lies in measurement. Sample measurements taken for the purpose of determining exposure to ceiling limits should be collected during periods of maximum expected concentrations. A sampling period of 15 min is recommended, with a minimum of three measurements per work shift, with the highest of the three measurements used as the estimate of the employee's upper exposure for that shift.[5] In many cases the work process appears relatively constant during the shift, and random sampling techniques are required to estimate the upper bounds of exposure. For example, to identify at least one 15-min period from those representing the top 20% of exposures with a 0.95 confidence level, eleven 15-min (nonoverlapping) samples need to be collected.[6] Unfortunately, total aerosol sampling and gravimetric analysis techniques may not provide adequate sensitivity to reliably monitor exposures at a level of 2.0 mg/m³ during a 15-min sampling period.[6]

As an alternative to conventional sampling and analysis using pumps and filters with subsequent gravimetric analysis, real-time measuring instruments could be utilized. Aerosol photometers represent a class of real-time aerosol instruments that are reliable, easy to use, and relatively inexpensive. These instruments sample the workroom air and instantaneously measure the concentration of airborne dusts and mists by measuring the amount of light scattered by these materials. Although the results of these measurements are typically displayed in milligrams per cubic meter, these numbers are estimates of the true concentration, as the amount of light scattered depends on the characteristics of the specific aerosol in addition to its concentration. The response of aerosol photometers also depends

on the physical configuration of the light scattering element and the wavelength of light used. Thus, it is generally recommended that these instruments be calibrated by comparison with gravimetric techniques. Laboratory calibration is not feasible for most industrial hygienists, given the cost of the specialized generation apparatus and exposure chamber, but field calibration may be viable.

Although conceptually simple, field calibration of the aerosol photometer results in some practical difficulties. Some instruments employ an internal filter or attachment for the purpose of calibration. The manufacturer of the instrument used in this study recommends[7] that the monitor be run for a period of time sufficient to collect a mass of at least 1 mg on the filter to permit accurate weighing. For concentrations equal to the NIOSH REL for MWFs (0.4 mg/m³), that translates to nearly 24 hours of operation. The manufacturer further recommends that the calibration factor be calculated by the ratio of the gravimetric mass concentration to the TWA determined by the instrument. The calibration is recommended to be repeated several times (at least three), preferably (but not necessarily) at differing concentrations, and the average calibration factor used.

METHODS

This study was undertaken (1) to determine the temporal nature of the exposure in machining operations and (2) to examine the relationship between the aerosol photometer measurements and traditional sampling methods. Real-time air monitoring using an aerosol photometer (DataRAM, MIE Inc., Bedford, Mass.) was performed at 23 plant sites. These plants were a subset of 79 small machining shops using MWFs being studied by NIOSH to assess the range of worker exposures associated with a variety of existing engineering controls. Shops were selected for study that represented a range of

a) Plant with lowest mean

b) Plant with highest peak
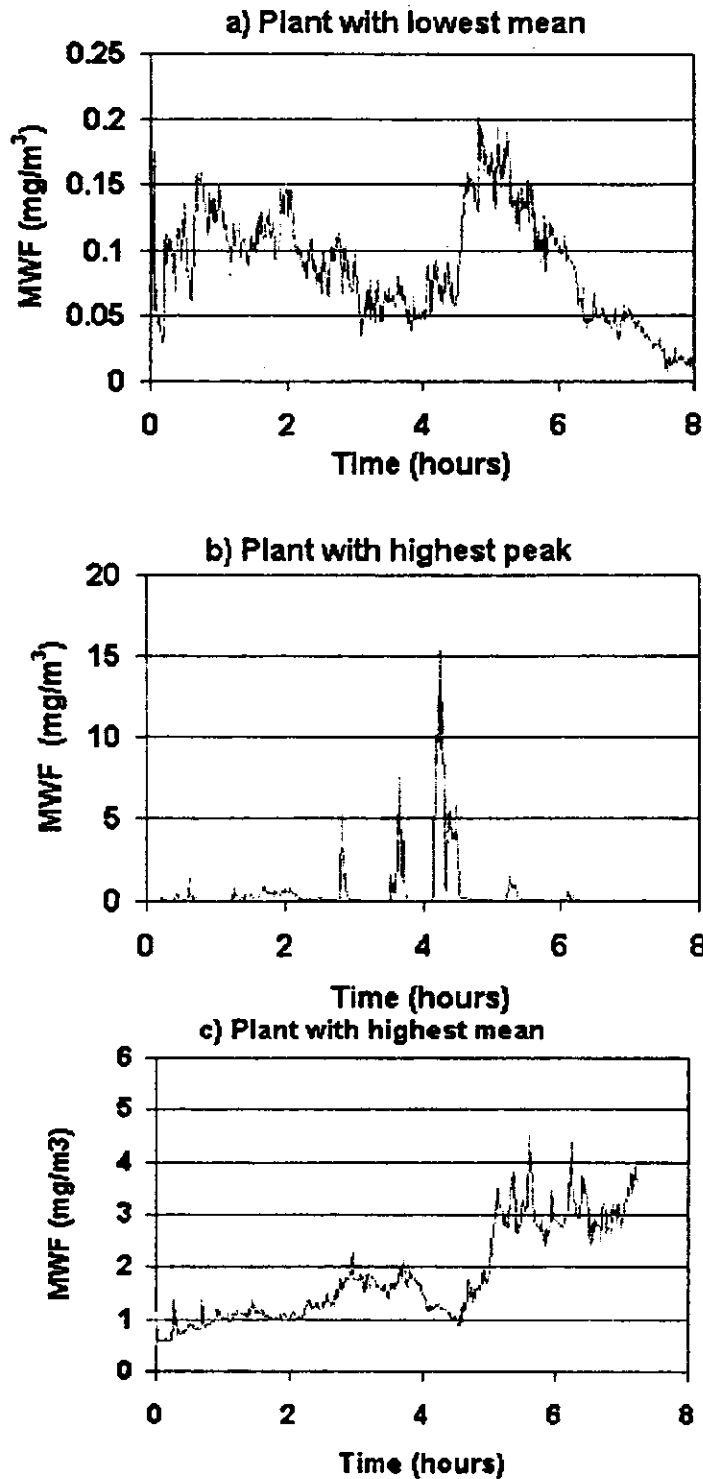

c) Plant with highest mean

FIGURE 1. Real-time MWF concentrations in plants with (a) lowest mean, (b) highest peak, and (c) highest mean levels.

sizes, machining operations, machine age, fluid types, and engineering controls. Real-time measurements were made in parallel with co-located filter samples using plastic sampling cassettes with and without the presence of a thoracic cyclone.

Real-Time Monitoring

The aerosol photometer was operated in a fixed location in each of the plant sites for approximately an 8-hour shift. The specific

TABLE II. Regression Analyses

Aerosol Photometer Versus:	Observations	r²	Slope^A
Thoracic (gravimetric)	23	0.68	0.64
Thoracic (extractable mass)	23	0.67	0.56
Closed-face cassette (gravimetric)	23	0.44	0.82
Closed-face cassette (extractable)	23	0.46	0.72
Thoracic (total mass)			
Straight oils	13	0.64	0.69
Water-based fluids	10	0.63	0.47

^A For the single parameter linear regression, the slope = the calibration factor.

instrument used had internal data logging capabilities and was operated at an instrument averaging time of 10 sec, with a 1-min logging period. For each logging period the instrument stored the clock time, the peak concentration measured during the logging period, and the average concentration for that period. The logged data were subsequently downloaded into a personal computer and imported into a commercial spreadsheet (Excel®, Microsoft Corp., Redmond, Wash.), for the calculation of 15-min running averages and the time-weighted average.

Thoracic MWF Aerosol

Samples for the thoracic fraction were collected using a cyclone preseparator (Model GK2-69, BGI Inc.) with a tared Teflon® filter (37mm diameter; 2 µm pore size) in three-piece open-face polystyrene filter cassettes at a flow rate of 1.8 L/min (BGI subsequently revised this to 1.6 L/min). These samples were analyzed for both "total" and "extractable" mass in accordance with a provisional method for metal removal fluid aerosol developed by

NIOSH and ASTM (the American Society for Testing and Materials). This method is intended to differentiate the MWF-specific components of the collected particulate from the non-MWF fraction (including metals and "background" particulate).[8]

Closed-Face MWF Aerosol

Air samples for total aerosol were collected using tared Teflon filters (37mm diameter; 2 µm pore size) in two-piece closed-face polystyrene filter cassettes at a flow rate of 2.0 L/min. These samples were analyzed for both total and extractable mass as previously described.

Data Analyses

Regression analyses were performed to determine the correlation of the results of the TWA aerosol photometer measurements with those obtained by the filter-based methods in all 23 plants. The initial data analyses consisted of a simple one-parameter (slope only) linear regression. The data set was subsequently divided into straight oil and water-based fluid subsets and the regression repeated. Additional analyses were performed using two-parameter (slope-intercept) linear regression and two-parameter regression of the log-transformed data, to examine the reduction in the error associated with the more sophisticated calibration schemes.

RESULTS

Straight oils were the predominant fluids used in 13 of the 23 plants, with the balance roughly an equal mix of soluble oils
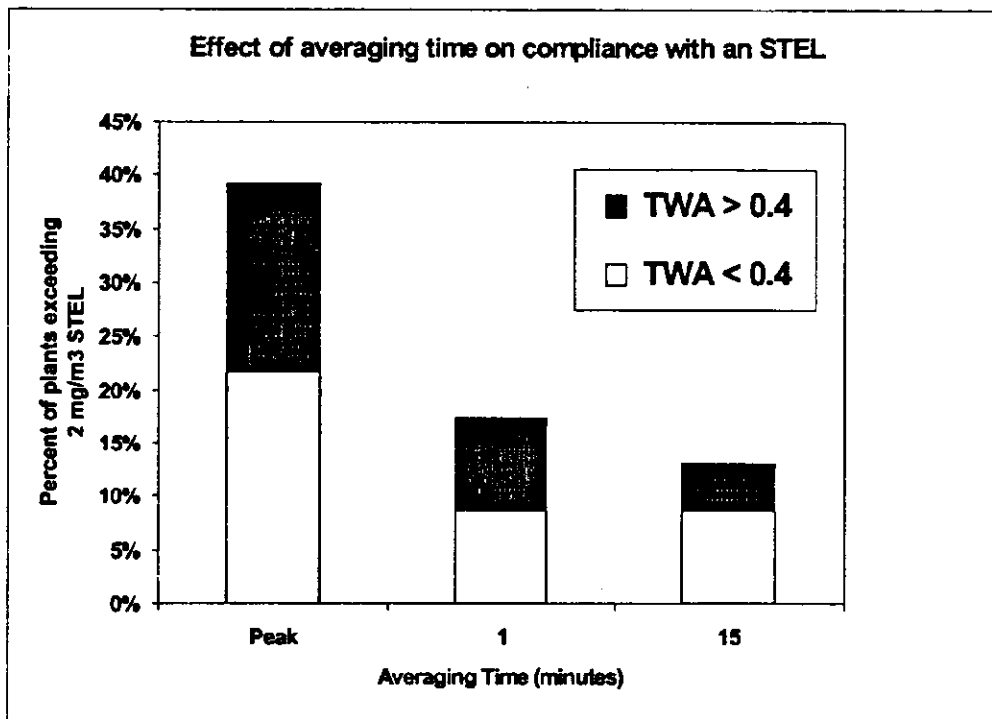

FIGURE 2. The percentage of plants with short-term concentrations exceeding 2.0 mg/m³ as a function of averaging time. Short-term concentration measured by an aerosol photometer using a calibration factor of 0.5 for water-based fluids, 0.7 for straight oils. TWA measurements based on sampling the thoracic fraction of the total aerosol mass.

TABLE III. Analysis of MWF Concentration Excursions

| Fluid Type | Peak (15 min) Concentration (mg/m³)[A] | | | Comments |
	GM	GSD	MAX	
Semisynthetic	0.07	4.7	3.62	Excess variability (GSD > 2); 15 m peak > 2
Semisynthetic	0.10	1.1	0.14	
Semisynthetic	0.44	1.3	0.72	
Semisynthetic	0.51	1.3	0.74	
Soluble oil	0.02	1.5	0.03	
Soluble oil	0.04	1.8	0.08	
Soluble oil	0.05	1.8	0.15	
Soluble oil	0.17	1.6	0.30	
Synthetic	0.07	1.4	0.19	
Synthetic	0.08	1.7	0.23	
Straight oil -	0.07	1.7	0.20	
Straight oil	0.07	1.3	0.14	
Straight oil	0.19	2.5	0.87	Excess variability (GSD > 2)
Straight oil	0.24	1.3	0.33	
Straight oil	0.24	1.6	0.52	
Straight oil	0.26	1.4	0.60	
Straight oil	0.40	2.0	0.79	
Straight oil	0.43	1.2	0.69	NIOSH REL exceeded
Straight oil	0.50	2.0	2.76	15 m peak > 2
Straight oil	0.61	1.4	0.91	NIOSH REL exceeded
Straight oil	0.81	1.6	1.30	NIOSH REL exceeded
Straight oil	0.83	1.4	1.50	NIOSH REL exceeded
Straight oil	1.14	1.6	2.46	NIOSH REL exceeded; 15 m peak > 2

[A]Using calibration factor of 0.5 for water-based fluids, 0.7 for straight oils

(4), synthetics (3), and semisynthetics (3). Table I contains a summary of statistics for the data collected by the aerosol photometer and by the filter-based methods. Concentrations ranged from 0.04 to 1.15 mg/m³, as determined by the thoracic-gravimetric method. The thoracic samplers measured about 75% of the amount determined by using closed-faced cassettes. The solvent extractable content of the thoracic samples and the closed-faced cassettes averaged 77 and 81%, respectively.

The TWA for the aerosol photometer was the average concentration recorded for the sampling period, which was approximately 8 hours. The peak (instantaneous) concentration reported in Table I was the highest value recorded at any time by the aerosol photometer during the 8-hour sampling period. The peak (1-min)

concentration reported is the maximum value obtained by examination of the 1-min averages. A 15-min running average was calculated from the 1-min averages, and the highest value determined is reported as the peak (15-min concentration). The data in Table I show that the magnitude of the peak concentrations decreases as the averaging time increases.

Temporal Variation

Figure 1 displays real time aerosol concentration records from the plants with the lowest average concentration, the highest peak concentration, and the highest average concentration. In a few plants (Figure 1c, for example) an increase in concentration occurred through the work shift, with a midshift (lunch) dip in mist

TABLE IV. Errors Associated With Various Calibration Methods for an Aerosol Photometer

| Calibration Method | Straight Oils | | Water-Based Fluids | |
	r²	Max Error %[A]	r²	Max Error %[A]
Uncorrected factory calibration	NA	134	NA	160
Average ratio: filter/Instrument TWA	NA	98	NA	105
Ratio = .85 (straight oil)				
Ratio = .79 (water based)				
Linear regression (single parameter)[B]				
y = 0.69·x (straight oil)	0.64	61	0.63	60
y = 0.47·x (water based)				
Linear regression (two parameter)[B]				
y = 0.59·x + 0.10 (straight oil)	0.67	72	0.88	60
y = 0.34·x + 0.09 (water based)				
Linear regression (two parameter, log transform)[B]				
ln(y) = 0.74·ln(x) − 0.56 (straight oil)	0.75	54	0.91	41
ln(y) = 0.70·ln(x) − 0.75 (water based)				

[A]The maximum absolute difference between the predicted concentration using the indicated calibration method for the aerosol photometer and the gravimetric determination for any one sample in the data set
[B]Where y = concentration measured using thoracic/gravimetric method and x = TWA concentration measured by aerosol photometer.

levels. In most plants there were no easily recognizable patterns in the concentration records. There was no attempt to reconcile production activities with the measured mist levels.

Relationship Between Exposure Measurements

A summary of regression analyses performed to determine the correlation of the results of the TWA aerosol photometer measurements with those obtained by the filter-based methods is included as Table II. The aerosol photometer data correlated best with that obtained with the thoracic sampler (gravimetric analysis). Because aerosol photometers respond in proportion to the sum of the volume of the individual particles, the instrument will measure any water contained in the MWF as mass. However, gravimetric techniques measure only the residual, nonvolatile particles retained on a filter. Thus, regression analyses were repeated, dividing the data into straight oil and water-based fluid subsets. These analyses were performed for the aerosol photometer—thoracic/gravimetric samplers only. The regression was performed forcing the calibration (regression) line through the origin, as it results in the calculation of a single parameter that could be used to calibrate the instrument.

DISCUSSION

Temporal Variation

Use of any real-time monitor requires that either the peak (instantaneous maximum) be measured, or that other "peaks" be calculated based on some preselected averaging time. Figure 2 illustrates the percentage of plants with short-term MWF mist concentrations that exceed 2.0 mg/m³. Depending on the averaging period used, short-term concentrations exceeded 2.0 mg/m³ in 13 to 39% of the plants studied. The peak concentrations measured in this study demonstrate that workers in machining plants may be exposed to peak exposures well above the NIOSH REL of 0.4 mg/m³ (thoracic-gravimetric). Examination of Figure 2 reveals that high short-term exposures were about as likely to be found in plants with average concentrations below the NIOSH REL as those above. NIOSH has noted[1] that some workers have developed work-related asthma, hypersensitivity pneumonitis, and other adverse respiratory effects at levels below the REL. Although the pathogenesis of these respiratory effects is not well understood, it is likely that mechanisms involving irritant or inflammatory effects may be involved. It is plausible that repetitive, intermittent, "peak" exposures to MWF aerosol may be related to irritant-induced asthma or asthmatic symptoms.[9]

ACGIH recommends that excursions above TWA concentrations be controlled even when the TWA level is within the suggested limits. Their recommendations are based on statistical considerations: short-term exposures generally are distributed lognormally, with geometric standard deviations (GSDs) mostly in the range of 1.5 to 2.0. If the GSD exceeds 2.0, the process is not "in control" and efforts should be made to restore "control." To examine the variability of the real-time data, the peak (15-min) concentration data were log-transformed, and the geometric means and GSDs computed. The results of these computations are presented in Table III. In 4 of the 23 plants there was excessive variability in the MWF concentration, as evidenced by short-term concentration GSDs of 2.0 or greater. In two plants this resulted in peak concentrations above 2.0 mg/m³ even though the TWA concentration was below 0.4 mg/m³.

Relationship Between Exposure Measurements

Given the desirability of monitoring short-term exposures using an aerosol photometer, how should the results be interpreted? That the aerosol photometer is most closely correlated to the thoracic fraction of the aerosol mass is not surprising. The instrument response curve for this instrument lies somewhere between the definitions of the respirable and thoracic deposition curves.[10] The aerosol photometer response drops with increasing particle size; thus it "sees" fewer large particles than the cassette and filter. The thoracic mass relative to the total particulate (as determined by a closed-faced cassette sampler) was about 0.75, similar to the value adopted by NIOSH[1] for the thoracic-to-cassette ratio (from the data of Woskie et al.[11]).

As the aerosol photometer measures all material present in its sensing volume, the calibration factors are smaller (by about 10%) for the analyses utilizing solvent extraction than for the gravimetric procedures. (The calibration factor is the ratio of the "true" concentration, as determined by a reference method—gravimetric, to that measured by the instrument.) This is slightly less than might be expected, as on the average the aerosols contained 20% extractable materials. The difference may indicate that the largest fraction of nonextractable material is either above or below the size range of optimum response for the instrument.

The manufacturer of the aerosol photometer used in this study indicates that the factory calibration will agree within ±20% with gravimetric measurements for most mineral dusts, indoor particulates, and ambient environments.[7] Field calibration through the use of an internal filter or collocated samples is recommended to achieve higher accuracy or in cases where the aerosol properties are expected to differ significantly from those of the factory calibration aerosol. Two physical properties of particles that are cited by the manufacturer as most often causing significant differences in response are density (as exemplified by certain liquid aerosols, specifically oil mists) and particle size <0.1 μm or >10 μm.[10] In the case of oil mists, the manufacturer notes that the aerosol photometer would tend to overestimate the concentration because the actual mass of oil particles (for the same size) is less than that of the calibration dust. The results of the regression analysis (Table II) indicate that this is indeed the case, as the slope of the regression line (the calibration factor) is 0.69 (0.54–0.84, 95% confidence limits) for the straight oils. Where water-based MWFs were utilized, the potential presence of unevaporated water in the aerosol particle is suggested as the cause of the larger overestimation. The slope of the regression line (the calibration factor) for the subset of water-based fluids was 0.47 (0.36–0.58, 95% confidence limits). This indicates that the aerosol photometer may significantly overestimate exposure to water-based fluids, unless field calibration is performed or another appropriate calibration factor for MWFs is employed.

Determining the Calibration Factor(s)

Once it has been decided that field calibration is needed, the method of determining the calibration factor(s) must be selected. As described earlier, the instrument manufacturer recommends[7] that the calibration factor be calculated by the average ratio of the gravimetric mass concentration to the TWA determined by the instrument. In the analyses utilized in this article, a one-parameter (slope only) linear regression was employed initially. This approach was used because of its simplicity and potential utility, as the aerosol photometer permits the operator to input an instrument calibration factor, allowing the corrected result to be read directly

from the display. Additional analyses were performed using two-parameter (slope-intercept) linear regression and a two-parameter regression of the log-transformed data. The latter analysis was utilized because real-time environmental data must be shown to be lognormally distributed.[12]

The calibration models developed were used to calculate a predicted concentration based on the aerosol photometer measurement. The percentage error between the predicted value and the gravimetrically determined concentration also was determined.

The results of these analyses are reported in Table IV. These analyses indicate that the use of an uncalibrated instrument can result in measurement errors as large as 160%; a calibration factor based on the simple average of the instrument response ratios may lead to errors as high as 100% (for these data). Increasingly sophisticated-calibration models result in better fit and smaller errors in prediction. Both two-parameter models share the disadvantage that a single calibration factor is unavailable for direct use with the instrument; a calibration curve would need to be utilized with the instrument.

The supposition of a constant calibration factor between real-time measurements and filter-based sampling particle size distribution is based on the assumption of a constant size distribution and physical/chemical composition for all samples. MWF aerosol size distributions for small machine operations (presented in a companion manuscript[13]) are surprisingly similar, with a mean mass median diameter of approximately 5 μm. Ideally, a calibration factor could be obtained for each combination of MWF and machining operation, an extremely time-consuming operation. In practice, the user may have more limited calibration data and should be cognizant of these assumptions and the potential errors in measurement.

CONCLUSIONS

Workers in small machining plants may be exposed to high peak concentrations of MWF aerosol, even in facilities where TWA exposures are below recommended exposure limits. Real-time monitoring to identify and eliminate the sources of these peak exposures may provide additional protection against adverse health effects. In addition, real-time monitoring can serve as a useful screening tool to indicate jobs or areas where additional sampling is warranted. The tendency of aerosol photometers to overestimate concentration provides a small margin of safety when measuring aerosols of MWFs. Use of a calibration factor of 0.7 for straight oils or 0.5 for water-based fluids may assist in the interpretation of aerosol photometer measurements if field calibration data are

not readily available. The calibration factors for aerosol photometers from other manufacturers or for instruments used under different conditions (for example, measurements within exhaust ducts) may differ significantly from those reported here. If field calibration is performed, use of one of the linear regression models can improve the accuracy over the calculation of a simple average calibration factor.

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