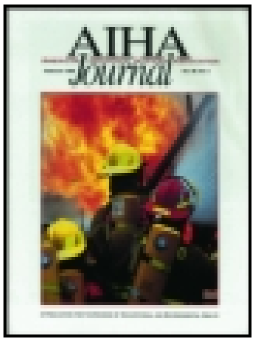

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Metalworking Fluid Exposures in Small Machine Shops: An Overview

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Sampling was conducted in 79 small machine shops to assess airborne exposures to metalworking fluids (MWFs). Measured exposures were compared with data from the literature and exposure criteria currently recommended by the National Institute for Occupational Safety and Health and the Occupational Safety and Health Administration MWF Standards Advisory Committee. Sixty-two percent of 942 personal samples collected were less than the recommended exposure limit (REL) of 0.50 mg/m^3 for total particulate. However, at least 1 sample exceeded the REL in 61 of the 79 facilities studied; 100% of the samples collected in 10 shops were greater than the REL. Similar trends were found for thoracic particulate exposures where 75% of 238 samples were below the thoracic particulate REL of 0.40 mg/m^3. The ratio between thoracic and total particulate for 238 paired samples was 0.55 (r^2=0.73). Workers exposed to straight fluids had the highest exposures (GM=0.67 mg/m^3) when compared with workers exposed to other classes of MWFs. The highest exposures were measured for grinding and hobbing (GM=0.67 and 0.60 mg/m^3, respectively). Measurements using personal impactors indicated that particle size distributions of MWF aerosols had an average mass median aerodynamic diameter of 5.3 μm. Straight oils and soluble fluids tended to be associated with larger particles than were other fluid types; grinding and turning produced the largest particles, whereas hobbing resulted in the smallest. In general, exposures were similar in magnitude and particle size to those previously reported in large automotive plants. Therefore, workers in these small shops may have risks of adverse health effects similar to those demonstrated in the automotive industry.

Keywords: machine shops, machining, metalworking fluids, oil mists, particle-size distributions, thoracic particulate

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Previously published studies of occupational exposures to metalworking fluids (MWFs) have most commonly described conditions in large machine shops, primarily in the automobile industry.[1–10] In general, metalworking operations in automotive plants change only infrequently, involve several high-production machining lines, and require high volumes of MWFs. Exposures to MWFs during automotive parts production have been reported to be affected by several factors, including fluid type and application method, machine type and age, cutting speed, engineering controls (including machine enclosures and local exhaust ventilation systems), and maintenance.[9]

Little is known about the extent of occupational exposures to MWFs in small machining shops (i.e., companies with fewer than 500 employees). It is estimated that 70–80% of the workers exposed to MWFs are employed in these shops.[11] Commonly known as "job shops," these facilities generally have fewer machining tools and use much lower quantities of MWFs than machining departments in automotive plants. Also, these shops are more likely to machine a variety of products according to different customer orders, and therefore frequently change machining parameters, which include metal and fluid types.

Because of the paucity of information on occupational exposures in small shops, the National Institute for Occupational Safety and Health (NIOSH) has conducted a cross-sectional study in 79 machine shops to measure personal exposures to MWFs. This study was intended to assess

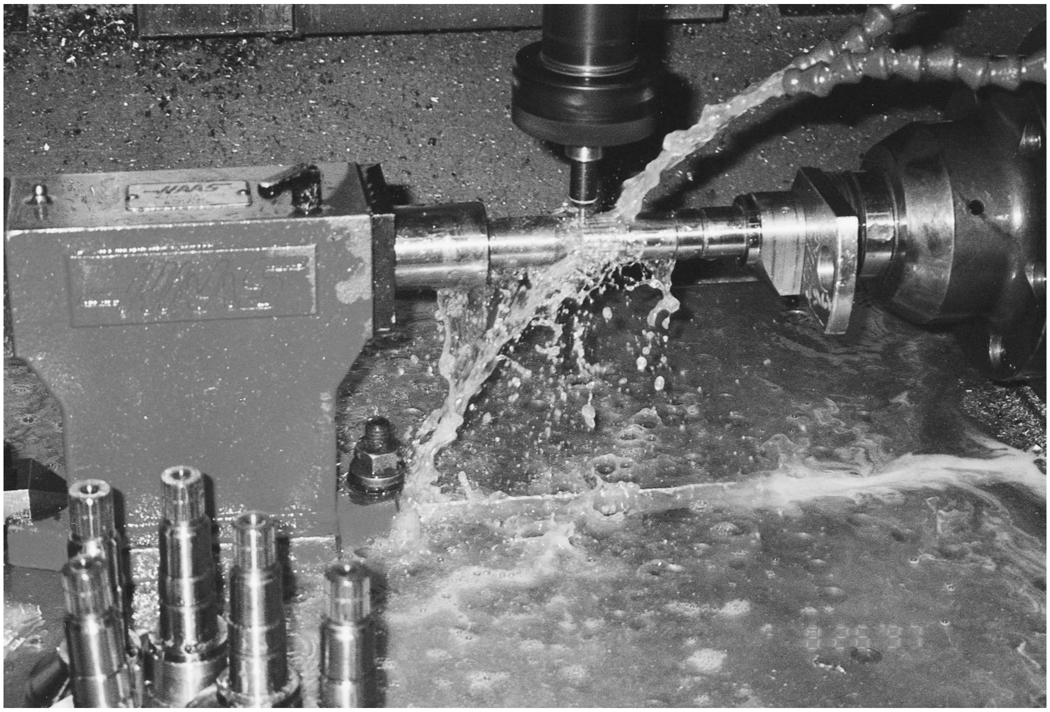

FIGURE 1. Photograph of an MWF "flooding" the cutting zone of a machining operation

MWF exposures in a representative sample of small machine shops relative to current and proposed exposure standards. Study results also may be useful for estimating the potential for associated health effects and the needs for future evaluation and control of MWF exposures. This article provides an overview of these study findings.

BACKGROUND

MWFs are widely used in machining operations such as drilling, grinding, turning, and milling. The principal functions of these fluids are to cool the tool and/or workpiece, to reduce friction between the tool and workpiece, and to flush away metal chips and swarf generated during the machining process. By reducing heat generation and tool wear, MWFs allow for significantly faster machining speeds and therefore increased production rates.[12]

MWFs generally are grouped into four major categories based on their composition. Straight or "insoluble" oils are generally derived from mineral (petroleum), marine (whale and fish), animal (lard and tallow), or vegetable sources and are not diluted with water. These oils are comprised mainly of long chain alkanes, C_{14} to C_{30}, and often supplemented with sulfurized, chlorinated, or phosphated additives to improve lubrication and heat dissipation capabilities.[12] Soluble or "emulsified" oils are emulsions of mineral/fatty oils that are diluted with water—typically 20–50%. Semisynthetic oils are similar to soluble oils but contain a lower concentration of oils (generally 5–20%) in the emulsion. Finally, synthetic oils do not contain any petroleum oil but rather are chemical solutions of organic or inorganic salts in water. A variety of chemical additives may be used in formulating MWFs to improve lubricity, prevent microbial growth, and inhibit corrosion.[12,13]

Metal cutting operations include drilling, turning, milling, hobbing, and broaching. These operations are characterized by the motion of the cutting tool and the workpiece. In drilling, holes are cut in a stationary or moving workpiece by the action of a sharp-edged rotating tool or drill bit. For deep holes, the MWF is often fed through passages in the drill bit at an elevated pressure. In turning, the workpiece rotates about its axis as a single-point cutting tool produces circular or conical surfaces as it moves parallel (or at a fixed angle) to the workpiece axis. If the cutting tool removes material from internal surfaces, the turning operation is termed boring. In milling, a rotating single or multipoint cutting tool produces flat surfaces or grooves as the workpiece moves in a line or series of parallel motions. Hobbing is a process used to make gears in which a complex cutting tool and the workpiece both rotate. In broaching, a multipoint tool resembling a file produces flat surfaces on the workpiece. Metals also can be shaped by grinding. In grinding, an abrasive wheel produces the cutting action. Grinding can be used to produce either flat or round surfaces, depending on the motion of the wheel or the workpiece.[14]

MWF can be delivered to the tool–workpiece interface either manually (by brush, spray, or dripping) or by an automated system (which includes flood, mist, and high-pressure spray or jet methods). Flooding, in which the fluid is pumped at low-pressure through a nozzle or nozzles directed at the cutting zone, is the most common application method (see Figure 1). Application of MWFs during the machining process creates an aerosol generated by (1) mechanical forces produced by the moving tools and/or workpiece; (2) condensation of fluid vapors formed by heat in the cutting zone; and (3) misdirected or extraneous spraying of fluids directly into the air.[13]

Machine enclosures, local exhaust ventilation, and mist collectors are sometimes used to reduce MWF aerosol in the work environment. Fully or partially enclosing the machine's cutting zone provides a physical barrier between the mist generation source and the worker. Local exhaust ventilation (LEV) can be used with or without an enclosure to capture MWF mists near their source; captured mists are generally discharged to the outdoors or recirculated within the work area after filtration. Mist collectors, such as filtration or electrostatic precipitation devices, can be used as an integral part of an LEV system or used as separate units, generally above emission sources, to remove MWFs from the air. In most machine shops the cleaned air is then recirculated into the general work environment.

In most small machine shops, individual machine sumps are most commonly used for simply recycling the used MWFs; these sumps generally have less than a 50-gallon capacity. In contrast, MWFs in automotive plants are usually transported through infloor troughs to a central tank or ‘‘sump’’ where the fluid is filtered, treated, and recycled back to the machining tools. Central fluid systems can range in size from a few hundred gallons to over 100,000 gallons.

Workers are most commonly exposed to MWFs by inhalation of aerosols and through skin contact. An estimated 1.2 million workers in the United States potentially are exposed to MWFs.[15] Occupational exposures to MWFs have been associated with a variety of respiratory conditions including hypersensitivity pneumonitis, chronic bronchitis, impaired lung function, and asthma.[2–4,6,10,16–25] Dermal exposures to MWFs are associated most commonly with allergic and irritant dermatitis.[26–32] There is some evidence that past exposures to some MWFs are associated with increased risk of some types of cancer.[33–37]

To reduce the potential health risks associated with MWFs, NIOSH currently recommends that occupational exposures to MWF aerosols be measured as thoracic particulate mass and limited to 0.4 mg/m^3 as a time-weighted average for up to 10 hours per day during a 40-hour workweek.[38] Recognizing that thoracic samplers may not be commonly available or used, NIOSH also recommends an equivalent total particulate mass limit of 0.5 mg/m^3 (based on a correction factor of 1.25 derived from data of Woskie et al.).[8] The Occupational Safety and Health Administration (OSHA) presently regulates occupational exposures to MWFs as ‘‘mineral oil mists’’; the current permissible exposure limit (PEL) for mineral oil mists is 5 mg/m^3 as an 8-hour time-weighted average.[39] In 1999 the OSHA Metalworking Fluids Standards Advisory Committee, an external committee representing labor, management, and public interests, submitted a report that included recommendations for a PEL of 0.4 mg/m^3 for thoracic particulate (and 0.5 mg/m^3 total particulate), systems management (i.e., a holistic approach for managing MWFs and machining processes that result in improved exposure control and enhanced productivity), medical surveillance, and training.[40]

METHODS

Facility Selection

Industries within four specific two-digit Standard Industrial Classification (SIC) codes (SIC 34–37) were targeted for study because these SICs account for an estimated 98% of all metal removal machines in the United States.[41] Approximately 25 machine shops were selected from each of 3 different geographic regions, including states in the West, Midwest, and Northeast. Business directories, listings from trade associations and unions, and referrals from state health and safety consultation programs were used to identify potential study sites within each region. Identified shops were randomly contacted by telephone to determine eligibility (i.e., employed fewer than 1000 employees and used MWFs) and to solicit participation, if eligible. Efforts were made to select facilities that represented a variety of machining processes, SICs, fluid and metal types, engineering controls, and workforce sizes.

Field Surveys

Surveys were conducted between January 1997 and January 1998. For consistency, the same two industrial hygienists conducted all field surveys, with support provided by field technicians as needed. A 2-day survey was conducted at each shop. On the first day, information was collected concerning the work force, machining processes, MWFs, and the on-site health and safety program. Full-shift air samples were collected on the second day of each survey.

Air Sampling

Full-shift breathing zone samples were collected on up to 20 machinists in each shop. If there were more than 20 machinists, workers were selected who operated machines that were representative of the different processes, fluid types, and engineering controls present.

Samples were collected and analyzed using NIOSH Method 0500 for total dust.[42] The sampler consisted of a tared Teflon® filter (37mm diameter; 2 μm pore size) in two-piece closed-face polystyrene filter cassettes; the sampling flow rate was nominally 2.0 L/min. Samples were analyzed gravimetrically for ‘‘total’’ mass. In addition, the ‘‘extractable’’ mass was determined by a provisional method (ASTM P42–97) developed by ASTM Committee E34.50 for separation of MWF from cosampled material.[43] This method involves an extraction procedure using a ternary solvent blend of methylene chloride, methanol, and toluene. The MWF-specific components of the collected particulate generally are soluble in this blend and therefore separated from the nonsoluble fraction, which may include metals and ambient dusts. An evaluation of this method is discussed by Glaser et al.[44,45]

Personal samples also were collected for the thoracic size particulate (i.e., those particles nominally less than ~10 μm in aerodynamic diameter, which are capable of passing the larynx and into the lungs). A cyclone preseparator (Model GK2.69, BGI Inc., Waltham, Mass.) was used with a tared Teflon filter (37mm diameter; 2 μm pore size) in a three-piece open-face polystyrene filter cassette at a flow rate of 1.8 L/min to achieve a D_{50} cut of 10 μm. The thoracic particulate samplers were worn by up to five workers in each facility who were also wearing a total particulate sampler. These samples were analyzed for both total and extractable mass as previously described.

Particle Size Distribution

Samples of MWF aerosol were collected using a Marple Personal Cascade Impactor (Model 294, Graseby Andersen, Smyrna, Ga.) to determine particle size distributions of sampled aerosols associated with different machining variables. Up to four personal samples were collected in each shop. A two-stage configuration was used (stages with cut points of 9.8 and 3.5 μm with a backup filter) with preweighed mylar filters and a sampling rate of 2 L/min; each collection filter was analyzed gravimetrically to determine particulate mass. Samples were not included in the reported data if less than the analytical limit of detection (30 μg) were collected on any stage. The mass median diameter (MMD) and geometric standard deviation (GSD) of the particle size distributions were estimated from linear regressions of the probit of the

TABLE I. Description of Machine Shops

	West	Midwest	Northeast	All	
Number of shops	28	30	21	79	
Number of shops with labor union	7	4	0	11	
				Mean	Range
Avg number of employees per shop	152	155	60	128	2–850
Avg number of machinists per shop	41	60	32	46	1–212
Avg number of machines per shop	33	61	39	45	2–180
Avg age of machines (in years)	20	26	29	26	0.02–99
Avg area of shop in ft^2	35,400	44,100	26,000	36,200	1200–320,000
Avg number machines per 1000 ft^2	1.6	1.6	3.0	1.96	0.07–10
Avg number machines per 1000 ft^3	0.08	0.09	0.3	0.13	0.01–1.0
Avg amount MWFs used (gals/yr)	2,740	6,400	3,160	4,260	15–29,760

cumulative distribution function versus logarithm of the cut diameters.[46,47] The MMD of the particle size distribution was considered to be that diameter corresponding to a probit value for the 50th percentile (probit=0), whereas the GSD was calculated by dividing the 75th percentile value (probit value=1) by the MMD. All statistical analyses were performed using the Statistical Analysis System (SAS) V6.12.[48]

Additionally, a portable dust monitor (GRIMM Dust Monitor, Model 1.105, Grimm Labortechnik GmbH & Co., Ainring, Germany) was used to measure particle size distribution and concentration on a real-time basis during distinct machining activities. The Grimm Monitor is an optical particle counter that classifies individual particles based on light scattering; the amount of light scattered is proportional to the size of the particle. The aerosol concentration is estimated by measuring the quantity of light scattered from all particles in the sensing chamber. An algorithm is used to calculate the mass of particles in each of eight discrete size intervals, ranging from >0.5 μm to >15 μm. Several 1-min measurements were made in the vicinity of operator workstations in each of the facilities studied. These measurements were stored in the instrument memory and subsequently downloaded to a personal computer. From each size distribution measurement, the particle MMD and the GSD were calculated.[46,47]

Data Analyses

Field sampling data were compiled into a database (Microsoft® Access 97, Microsoft Corp., Redmond, Wash.). MWF concentrations were assessed by evaluating the following characteristics: type of industry, geographic region, age of machine, type of machining operation, type of fluid, and type of control. Because mass concentration data were found to follow a lognormal distribution, all statistical analyses were performed on logarithmically transformed data. When more than two means were compared, multiple comparison methods employing the Bonferroni inequality were used to compare the individual means.

RESULTS

Shop Participation

A total of 400 shops were contacted to determine eligibility for study participation; responses were received from 355 shops (89%). Eighty-seven respondent shops were determined to be ineligible to participate (primarily because they were no longer using MWFs). Of the 268 eligible shops, 189 shops were not surveyed due to (1) management's refusal (n=179) or (2) scheduling conflicts (n=10). Overall, 79 (30%) of the eligible shops were studied.

Shop Demographics

Field surveys were conducted in approximately 25–30 machine shops in each of the following three geographic regions: West (including Seattle, Wash.; Portland, Ore.; Los Angeles, Calif.); Midwest (Chicago, Ill.; Cincinnati and Cleveland, Ohio; Indianapolis, Ind.), and Northeast (Buffalo, N.Y.; Providence, R.I.; Hartford, Conn.; Boston, Mass.). Participant shops represent 6 different 2-digit SIC codes (34–39) and 32 different 4-digit SIC codes. Because many of the machine shops studied were custom job shops in which the types of machined products frequently changed, shops were classified by SIC based on the primary products being machined at the time of the survey. Twenty-two of the 79 shops (28%) in this study manufactured screw machine products (SIC 3451); 6 shops were included in the next most frequently surveyed industry—aircraft parts and equipment manufacturing (SIC 3728).

Table I presents information about the 79 shops included in this study. There were slightly more shops studied in the West and Midwest than in the East; few shops had union representation. The total number of employees at each facility ranged from 2 to 850; the machinists per shop ranged from 1 to 212. The number of machine tools (both active and inactive during the survey) in each shop ranged from 2 to 180. On average, each shop purchased 4260 gallons of MWFs annually (ranging from 15 to 29,755 gallons). Shops in the Midwest generally had more machinists and used more MWFs than in the other parts of the country. Shops in the East tended to have a higher machine density (i.e., the number of machines per shop area) and used older machines than in the other regions. All of the shops included in this study were primarily operating machines with individual fluid sump systems (i.e., rather than being connected to a central sump system).

Personal Exposures

Personal exposures to total particulate (both total and extractable mass) were measured for 942 machinists from the 79 shops in this study. Time-weighted average exposures ranged from 0.05 to 10.4 mg/m^3 (total mass) and from 0.01 and 6.79 mg/m^3 (extractable mass). Figure 2 presents a cumulative distribution of exposures, which indicates that essentially all (99.8%) were less than the current OSHA PEL for mineral oil mist of 5.0 mg/m^3; 62% of the measured exposures were less than the NIOSH REL of 0.5 mg/m^3 for MWF total particulate mass. Results for the extractable mass concentrations also are shown in the stacked bar chart. As shown, a much higher percentage of extractable mass concentrations were less than 0.25 mg/m^3 (50%) compared with total mass concentrations (27%).

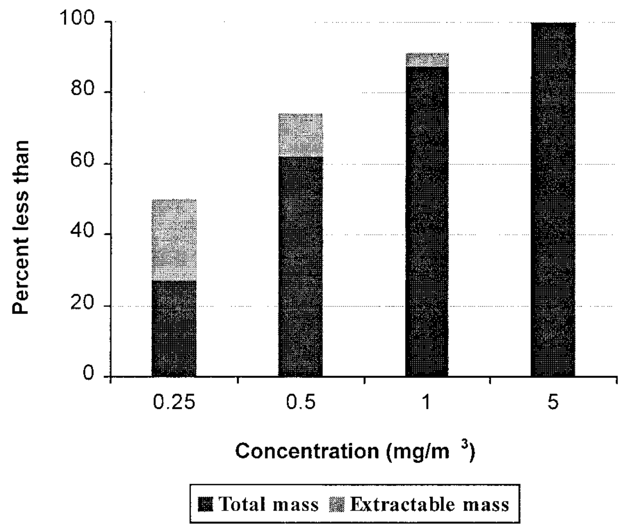

FIGURE 2. Distribution of 942 total particulate exposures

During sampling, most (70%) workers were observed to operate a single machine whereas 24% of workers simultaneously operated two or more machines (of either similar or different types of operation); the remaining 6% did not operate a machining tool. Exposures to total particulate among these three groups were not significantly different (GM= 0.41, 0.43, and 0.41 mg/m³, respectively).

Personal Exposures by Industry

Table II presents a summary of the total particulate exposure levels for those 23 four-digit SICs in this study in which a minimum of 10 personal samples were collected. The industries with the highest GM exposure levels were SIC 3643—wiring and electrical components manufacturing (GM 1.15 mg/m³); SIC 3566—speed changers, industrial speed drives, and gear manufacturing (GM=0.71 mg/m³); SIC 3452—bolts, nuts, screws, rivets and washers manufacturing (GM=0.66 mg/m³); and SIC 3541—metal-cutting machine tools manufacturing. When these particular SICs were compared with the five SICs in Table II with the lowest exposure levels, shops in the higher SIC group were more likely to use straight fluids, perform grinding and turning operations, use partial-enclosed machines, and use older machines (mean age of 30 years). Shops in the low-exposure SICs generally used soluble fluids, performed milling and turning operations, and used machines that were fully enclosed and only 14 years old. SIC 3643, which had the highest GM (1.15 mg/m³), was represented by one shop in which turning with straight oils and milling with soluble fluids were performed; all 15 samples collected in this shop were above 0.53 mg/m³ (12 were above 1.00 mg/m³).

Personal Exposures by Machine Age

Thirty-three percent of workers sampled in this study were machining with equipment at least 30 years old; 30% of personal samples were associated with equipment less than 10 years old, and 14% were less than 5 years old. The GM exposure level for workers using "old" machines (≥30 years old) was 0.48 mg/m³ compared with 0.34 mg/m³ for "new" machines (<10 years old); this difference was significant ($p < .05$).

Personal Exposures by Region

On a geographic basis, workers from shops in the Northeast had the highest total particulate exposure level (GM=0.56 mg/m³), which was significantly different ($p < .05$) from shops surveyed in the West (GM=0.39 mg/m³) and the Midwest (GM=0.39 mg/m³). Results for both total mass and extractable mass levels are shown by region in Figure 3.

Personal Exposures by Machining Operation

Personal exposures associated with 18 different machining operations were evaluated in this study; 76% of sampled workers were

TABLE II. Personal Total Particulate Sampler Mass Concentrations (mg/m³) by SIC

SIC—Industry	n	GM	GSD
3643—Electrical components, wiring	15	1.15	1.40
3566—Speed changers, high-speed drives and gears	55	0.71	1.79
3452—Bolts, nuts, screws, rivets, and washers	34	0.66	2.30
3541—Metal-cutting machine tools	55	0.51	2.62
3585—Refrigeration and heating equipment	19	0.49	1.38
3451—Screw machine products	290	0.48	2.08
3469—Metal stampings, NEC	53	0.46	2.32
3519—Internal combustion engines, NEC	29	0.45	2.26
3843—Dental equipment	11	0.44	2.16
3492—Fluid power valves and hose fittings	38	0.43	1.99
3553—Woodworking machinery	19	0.43	1.86
3556—Food products machinery	17	0.38	1.40
3546—Power-driven handtools	16	0.36	1.66
3714—Motor vehicle parts and accessories	27	0.34	1.66
3731—Ship building parts	21	0.31	1.71
3545—Cutting tools	12	0.29	2.11
3423—Hand and edge tools	19	0.29	1.57
3728—Aircraft parts, NEC	81	0.29	2.47
3544—Special dies and tools, die sets and jigs	23	0.26	1.53
3592—Carburetors, pistons, and valves	12	0.26	1.46
3555—Printing trades machinery and equipment	11	0.24	1.65
3491—Industrial valves	11	0.20	1.49
3494—Valves and pipe fittings, NEC	29	0.14	1.33

Note: For SICs with at least 10 samples; NEC = not elsewhere classified.

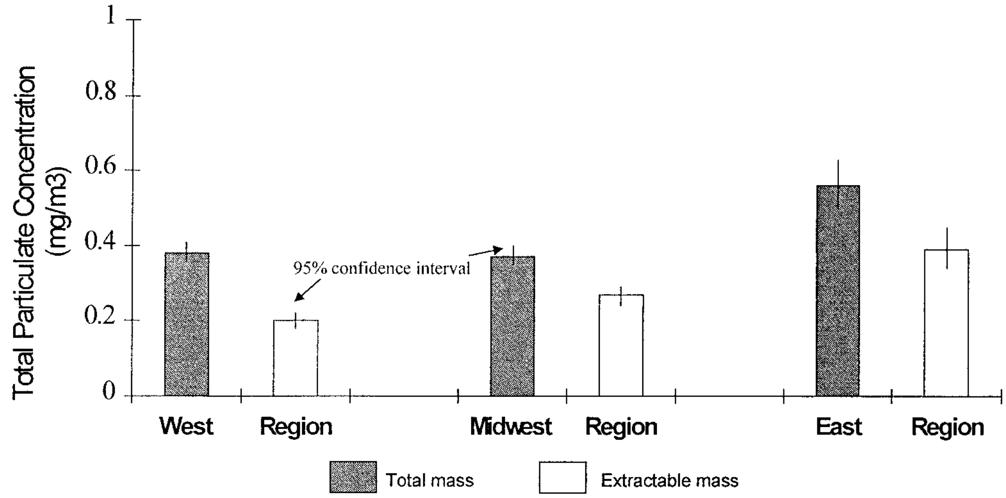

FIGURE 3. Total particulate GM exposures by geographic region

performing one of three primary operations: turning (n=412), milling (n=192), or grinding (n=119). Total mass and extractable mass exposure results for all operations with at least 15 samples are presented in Table III. Included are results for nonmachining jobs (i.e., the "non-MWF" category) in which a worker was located in the shop area and was involved in activities such as machine set-up or maintenance. Additionally, results are included for those workers who performed two or more different machining operations while tending multiple machines; these samples are grouped as "mixed" operations. The highest exposures were found for workers who performed grinding (GM=0.67 mg/m^3) or hobbing (GM=0.60 mg/m^3). Statistically, the geometric means for grinding and hobbing were the same; however, both were different ($p < .05$) from all of the other machining operations involving MWFs. Also shown in Table III is the percentage of samples in each process category that was greater than the NIOSH REL of 0.5 mg/m^3. Hobbing and grinding had the highest percentages (65 and 64%, respectively); drilling had the lowest (19%). Similar differences between operations are shown for the extractable mass concentrations. Generally, the extractable mass levels were 50–65% of the total mass levels; samples collected for drilling, sawing, and non-MWF operations contained the highest fraction of nonextractable material (45, 49, and 49%, respectively).

Table III also includes results of sampling in areas separated from the main work areas in each shop, such as break rooms or office areas. These areas were intended to be representative of the ambient levels of particulate in the shops without the contribution from MWFs. The total mass concentrations in these "background" areas ranged from 0.001 to 0.81 mg/m^3; the extractable mass ranged from 0.001 to 0.57 mg/m^3. In 5% of the shops, the REL for total particulate was exceeded in these areas, which had been judged to be free of airborne MWFs. Some possible reasons for this finding are discussed later.

Personal Exposures by Fluid Type

Total particulate exposure levels associated with each type of MWF are shown in Table IV. Machining activities using straight fluids were sampled most frequently (40%) followed by soluble (27%), semisynthetic (18%), and synthetic (12%) fluids. Thirteen samples (2%) were collected during machining without MWF and were classified as "dry." Most shops (79%) used at least two different fluid types. The highest exposures were associated with straight

TABLE III. Personal Total Particulate Sampler Mass Concentrations (mg/m^3) by Type of Machining Operation

		Total Mass				Extractable Mass			
Operation	N	GM	GSD	Min/Max	% >REL[A]	GM	GSD	Min/Max	% >REL[A]
Grinding	119	0.67	2.19	0.14/10.4	64	0.43	2.82	0.02/6.79	48
Hobbing	37	0.60	1.69	0.21/1.94	65	0.43	2.08	0.09/1.30	49
Turning	412	0.43	2.06	0.07/3.26	40	0.31	2.37	0.02/3.05	29
Lathes	152	0.33	1.99	0.07/3.19	25	0.21	2.31	0.02/2.03	14
Screws	260	0.51	2.00	0.11/3.26	46	0.39	2.22	0.02/3.05	36
Non-MWF	41	0.41	2.56	0.09/2.41	32	0.20	4.10	0.00/2.07	24
Sawing	16	0.35	2.22	0.16/1.98	25	0.17	3.23	0.04/1.84	25
Milling	192	0.33	1.93	0.05/2.67	22	0.18	2.00	0.02/1.32	5
Drilling	21	0.29	1.85	0.09/1.31	19	0.13	3.46	0.00/0.55	11
Stamping	19	0.28	2.27	0.06/1.10	32	0.18	2.44	0.05/1.05	12
Mixed	40	0.27	2.30	0.08/2.15	25	0.17	2.35	0.03/2.02	13
Background	61	0.06	4.01	0.001/0.81	5	0.04	3.56	0.001/0.57	2

Note: For operations with at least 15 samples.
[A]REL for "total" particulate is 0.5 mg/m^3.

TABLE IV. Results of Personal Total Particulate Sampler Mass Concentrations (mg/m^3) by Type of Metalworking Fluid

		Total Mass				Extractable Mass			
Fluid	N	GM	GSD	Min/Max	% >REL[A]	GM	GSD	Min/Max	% >REL[A]
Straight	359	0.52	2.09	0.06/10.4	50	0.39	2.38	0.00/3.88	40
Synthetic	106	0.45	2.05	0.09/3.76	46	0.24	2.99	0.02/2.03	31
Soluble	242	0.34	2.08	0.07/2.41	26	0.19	2.38	0.03/2.26	15
Semisynthetic	158	0.33	2.07	0.05/7.12	26	0.20	2.27	0.02/6.79	13
None (dry)	13	0.22	2.14	0.09/0.84	23	0.13	2.16	0.05/0.46	0

[A]REL for "total" particulate is 0.5 mg/m^3.

fluids (GM=0.52 mg/m^3) and synthetic fluids (GM=0.45 mg/m^3); mean exposures for these two fluids were statistically the same and were significantly higher than exposures measured for the other three fluid categories ($p < .05$). Approximately 50% of the total mass concentrations for straight fluids and synthetic fluids were greater than 0.5 mg/m^3. In general, the geometric means for extractable mass concentrations were 55–65% of the total mass concentrations.

Personal Exposures by Engineering Controls

Of the machines studied, 24% had a "full" or complete enclosure (i.e., a five-sided box or similar enclosure completely surrounding the machine cutting zone), 22% had a "partial" enclosure (three- or four-sided enclosure in which top and/or one side are open), and 38% used a "splash guard" (one- or two-sided wall between the cutting zone and the machinist); 16% of the machines had no engineering controls. Ninety-one percent of new (i.e., <10 years old) machines had an engineering control installed (full or partial enclosure or splash guard) compared with 82% of old machines (≥30 years old). For comparison, the average machining speed of new machines was two times higher than for the older machines (2000 rpm versus 1000 rpm). The total particulate exposure levels associated with the different control categories are presented in Figure 4. The lowest levels were measured for workers operating machines without any type of enclosure or splash guard (GM=0.36 mg/m^3); this group was statistically different from those machines with splash guards (GM=0.45 mg/m^3).

LEV was observed on 18% of all sampled machines. In this study, the only type of machine for which LEV was consistently used across all of the engineering control categories (i.e., full or partial enclosure, splash guard, or none) was screw machines. A comparison of exposure levels by control type both with and without LEV is presented for screw machines in Figure 5. Although the mean exposure for fully enclosed screw machines was reduced by 46% when LEV was used, this reduction was not significantly different. In this study the reductions in exposure levels due to the use of LEV were not statistically significant when compared with the same type of control without LEV.

Essentially all of the full and partial enclosures were OEM—original equipment installed by the machine manufacturer (100% and 97%, respectively). One-third (33%) of the splash guards on sampled machines were retrofitted—that is, designed and installed at the shop. The GM exposure level for machines with OEM splash guards was 0.50 mg/m^3; the GM for machines with retrofit splash guards was 0.38 mg/m^3 ($p < .05$).

Thoracic Particulate Exposures

Thoracic particulate exposures were measured for 238 of the same 942 machinists sampled for total particulate exposures. Figure 6 presents a cumulative distribution for thoracic particulate, which shows that 75% of exposures were less than the NIOSH REL of 0.4 mg/m^3 for thoracic particulate; 94% of thoracic samples were less than 1.0 mg/m^3.

Thoracic particulate exposures associated with different machining operations and MWF types are shown in Tables V and VI, respectively. As seen previously for total particulate exposures, the highest exposures were associated with hobbing and grinding operations (GM=0.42 and 0.36 mg/m^3, respectively) and with synthetic and straight fluids (GM=0.28 and 0.27 mg/m^3, respectively). In general, the trends in thoracic exposures by operation and fluid types were similar to those seen for total particulate exposures.

A two-parameter linear regression was performed comparing results obtained from the 238 paired personal thoracic and total particulate samplers. A graph of the mass concentration measured by the total sampler versus the thoracic sampler is shown in Figure

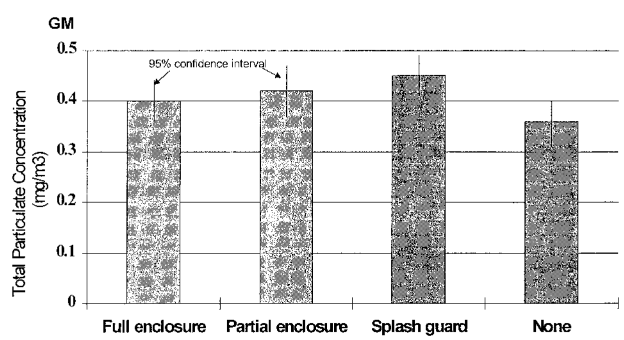

FIGURE 4. Comparison of GM exposures associated with different engineering controls

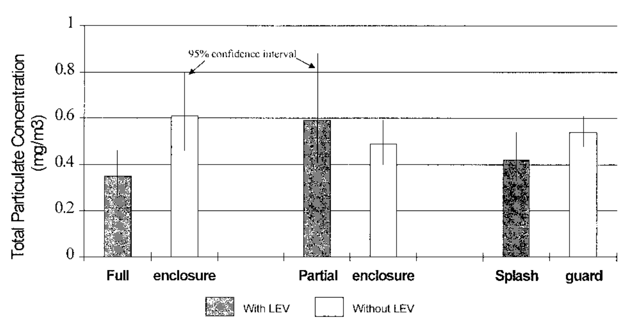

FIGURE 5. Comparison of GM exposures associated with different machine enclosures and the use of LEV (for screw machines only)

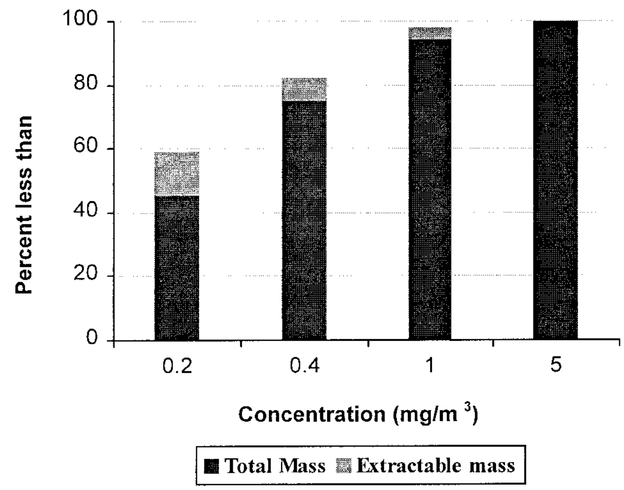

FIGURE 6. Distribution of 238 thoracic particulate exposures

7; separate plots for the total mass and the extractable mass concentrations are presented. Based on all paired samples, the mean ratio of thoracic to total particulate (calculated as the antilog of the intercept of the regression equation) was 0.55 ($r^2 = 0.73$) for the total mass concentration; the ratio was 0.52 (r^2=.50) for the extractable fraction.

Particle Size Distributions

A total of 169 personal impactor samples collected on machine operators were analyzed and used to estimate particle size distributions. The average particle size distribution by type of operation and fluid is shown in Table VII. For comparison, particle size distribution estimates of MWF aerosols in automotive plants as reported by Woskie also are included in this table.[8] The largest size particles were measured near grinding and turning operations—generally when straight oils or soluble fluids were used. The overall mean MMD measured across all operations and fluid types in this study was 5.3 μm (GSD=5.2); the mean MMD calculated from results reported by Woskie was 4.9 μm (GSD=2.5).

The Grimm Dust Monitor was used to sample particle size distributions in the vicinity of the same machines that were sampled using the Marple impactors. A comparison of these 105 "paired" results are shown by histograms in Figure 8. Also, a comparison of the MMDs and GSDs by operation and fluid type as determined by these two particle size samplers is presented in Table VIII. Overall, the mean MMD of the 105 Marple impactor samples was similar to that measured by the Grimm Dust Monitor (5.6 versus 4.5 μm). However, there was a much wider distribution of MMDs as determined from the impactor (range of 0.8–16.9 μm) compared with the Grimm instrument (range of 2.2–7.7 μm). Similarly, the range of GSDs was much greater for the impactor (2.0–22.1) than for the direct-reading instrument (1.6–3.6).

DISCUSSION

This article provides detailed information about occupational exposures to MWFs among a population of workers not previously studied. Most exposure studies of MWFs have been conducted among large automotive industry facilities in the Midwestern region of the United States. These automotive plants typically have corporate as well as site-specific health and safety staff, and well-described health and safety programs with infrastructure to carry out the programs. In this study, workers were included from at least 32 different industries located in three different geographic regions. The machine shops in this study tended to be owner-operated or small-business establishments that typically involved smaller buildings with fewer machines and workers than automotive plants. Also, these smaller shops generally did not have the financial resources or as many personnel devoted solely to health and safety issues such as worker training, exposure monitoring, medical surveillance, and engineering controls. Although the work environments and occupational health programs for MWF-exposed workers may be quite different between this study and those previously reported, the workplace exposure levels to MWFs are generally very similar.

Exposure data are available from several recent studies in which exposures to MWFs were evaluated in the automotive industry.[3,4,10] In general, the mean exposures to airborne MWFs during automobile component manufacturing have been reported to be less than 1.0 mg/m³. Kriebel reported mean exposure concentrations of 0.24 mg/m³ for aerosols of straight fluids and 0.22 mg/m³ for soluble fluids (using a "7-hole" inhalable fraction sampler).[4] Similar concentrations were reported by Greaves with mean concentrations (thoracic fraction) for several plant surveys ranging from 0.2–0.68 mg/m³ (straight fluids), 0.35–0.65 mg/m³ (soluble fluids), and 0.41 mg/m³ (synthetic fluids).[3] Likewise, Robins reported exposure to soluble MWF aerosols for automotive parts manufacturing workers that ranged from 0.10 to 0.60 mg/m³ (thoracic fraction).[22] Woskie, using the inhalable sampler,

TABLE V. Results of Personal Thoracic Particulate Sampler Mass Concentrations (mg/m³) by Type of Machining Operation

		Total Mass				Extractable Mass			
Operation	N	GM	GSD	Min/Max	% >REL[A]	GM	GSD	Min/Max	% >REL[A]
Hobbing	12	0.42	1.81	0.17/1.00	50	0.32	2.00	0.09/0.86	50
Grinding	33	0.36	1.95	0.12/1.10	42	0.22	3.61	0.00/1.00	33
Milling	53	0.22	2.17	0.06/1.10	25	0.10	4.37	0.00/1.09	15
Stamping	7	0.22	2.66	0.08/0.84	43	0.16	3.36	0.04/0.82	29
Turning	102	0.21	2.21	0.03/1.50	20	0.15	3.09	0.00/1.40	14
Lathes	37	0.17	2.23	0.03/1.20	8	0.11	3.07	0.00/0.57	5
Screws	65	0.24	2.15	0.05/1.50	12	0.17	3.04	0.00/1.40	15
Mixed	14	0.13	2.41	0.03/0.47	14	0.11	2.38	0.03/0.44	14

Note: For operations with at least five samples.
[A]REL for "thoracic" particulate is 0.4 mg/m³.

APPLIED STUDIES

TABLE VI. Results of Personal Thoracic Particulate Sampler Mass Concentrations (mg/m³) by Type of Metalworking Fluid

		Total Mass				Extractable Mass			
Fluid	N	GM	GSD	Min/Max	% >REL[A]	GM	GSD	Min/Max	% >REL[A]
Synthetic	31	0.28	2.06	0.10/1.10	29	0.18	2.53	0.04/1.00	19
Straight	81	0.27	2.16	0.06/1.50	31	0.18	3.90	0.00/1.40	25
Semisynthetic	41	0.23	1.99	0.07/1.20	22	0.16	2.10	0.05/0.72	17
Soluble	73	0.18	2.53	0.03/1.10	21	0.09	4.05	0.00/1.09	14
None (dry)	2	0.18	1.00	0.18/0.18	0	0.11	2.06	0.06/0.18	0

[A]REL for "thoracic" particulate is 0.4 mg/m³.

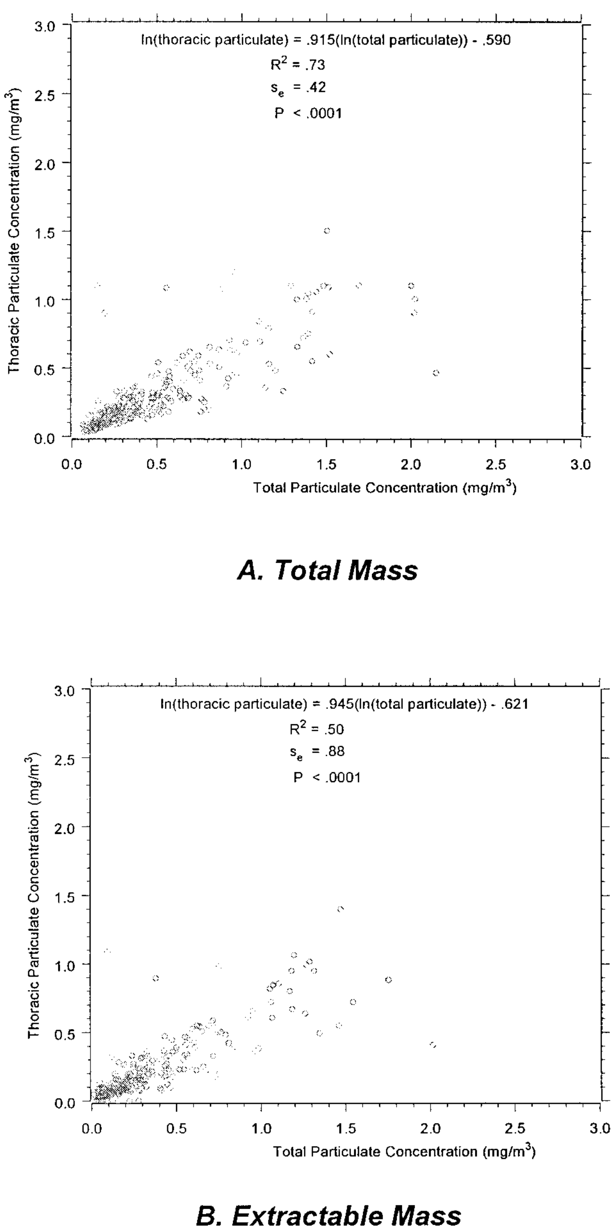

FIGURE 7. Plot of total particulate versus thoracic particulate concentrations for (A) total mass and (B) extractable mass

found slightly higher exposures to straight fluids (GM= 0.19 mg/m³) compared with soluble fluids (0.17 mg/m³); workers performing multiple drill and chucking operations had the highest exposures (GM= 0.25 and 0.20 mg/m³, respectively).[10]

Historical data on MWF exposures in a variety of industries also are available in the Integrated Management Information System (IMIS), an OSHA database of inspector-collected sampling results from 1979–present.[49] An examination of exposure data collected between 1979–95 demonstrates a steady decline in MWF-exposure concentrations over time. The arithmetic mean concentration for all samples collected during this time period was 0.92 mg/m³ (total particulate mass); for the period 1989 to 1994, the arithmetic mean was 0.49 mg/m³. Since 1989, 73% of measured airborne MWF concentrations have been less than 0.5 mg/m³ (compared with 40% between 1979–1989).

Data from this study are generally consistent with the cross-sectional OSHA IMIS compliance data. When comparing the present data with OSHA data collected during 1985–95 for the common 32 SICs, it was found that 65% of samples collected by OSHA were below 0.5 mg/m³ compared with 62% in the present study. Similarities are seen at other exposure levels as well. For example, 99.8% of samples in this study were less than 5 mg/m³ compared with 99.3% of the OSHA data. Overall, it appears that exposures measured in the present study are quite similar to those measured by OSHA, which requires mandatory participation of selected sites across all industries using MWFs. These similarities, as well as the targeting of those SICs in which the majority of MWFs are used, suggest that, despite the voluntary nature of cooperation in the present study, the resultant study population is quite representative of current occupational exposures to MWFs.

Overall, most exposures in this study were less than the NIOSH RELs for MWFs measured as total or thoracic particulate. However, high exposures were found in almost all 79 shops studied—61 shops (77%) had at least one personal exposure above 0.5 mg/m³ (Figure 9). In 10 plants, 100% of the samples collected for total particulate were above the REL. Of these 10 shops, 5 manufactured screw machine products (SIC 3451) and 2 made industrial speed drives and changers (SIC 3566); all were located in the East. As a group, these 10 shops generally used straight oils and performed turning operations more frequently than the other 69 shops in this study. Also, there was a higher machine density (3.0 versus 1.6 machines per 1000 ft²) and machines were slightly older (28 versus 22 years) in these 10 shops. All of these factors generally were associated with higher exposures to MWFs throughout this study. These results suggest that some machining situations, such as when performing turning with straight oils, are frequently associated with high MWF levels and may require focused and effective efforts to reduce exposures below 0.5 mg/m³.

Thirty-eight percent of the 942 total particulate samples collected in this study were above 0.5 mg/m³. Compared with the rest, these "high" exposures were more frequently associated with

TABLE VII. Average Particle Size Distribution Based on Marple Personal Impactor Samples by Operation and Fluid Type

		Small Shops			Automotive Plants(8)C		
Operation	MWF Type	N	MMD[A] (μm)	GSD[B]	N	MMD (μm)	GSD
Boring	synthetic	1	5.3	2.3			
Milling	straight	2	3.2	3.9			
	soluble	20	4.9	4.6	59	5.4[D]	3.2[D]
	semisynthetic	14	4.3	6.9			
	synthetic	2	4.6	13.6	25	6.0[D]	3.8[D]
Turning							
All	straight	63	6.0	5.0			
	soluble	15	5.3	4.7			
	semisynthetic	11	3.4	6.0			
	synthetic	2	2.2	8.1			
Lathe machine	straight	5	3.9	5.6			
	soluble	14	5.2	4.7			
	semisynthetic	9	3.6	6.4			
	synthetic	2	2.2	8.1			
Screw machine	straight	58	6.2	4.9	37	6.1	3.1
	soluble	1	6.7	4.8			
	semisynthetic	2	2.6	4.0			
Broaching	straight	1	4.5	2.5			
	soluble				6	5.8	3.2
Drilling	straight	1	3.7	3.8			
	soluble	1	3.7	9.6	33	5.4[E]	3.3[E]
Tapping	semisynthetic	1	5.1	6.1			
	synthetic				19	7.1[E]	2.6[E]
Hobbing	straight	6	2.7	5.4	48	3.9	2.4
Grinding	straight	3	10.2	7.9	13	5.7	2.5
	soluble	7	7.5	3.7	50	6.5	2.4
	semisynthetic	8	5.7	3.7	6	4.4	2.5
	synthetic	11	5.0	5.8	19	5.6	2.8
Overall		169	5.3	5.2	315	4.9	2.5

[A]Average mass median diameter.
[B]Average geometric standard deviation of the particle size distribution.
[C]A weighted average is presented when multiple values were reported.
[D]Results were grouped by machine type as "boring/milling/turning."
[E]Results were grouped by machine type as "drilling/tapping/reaming."

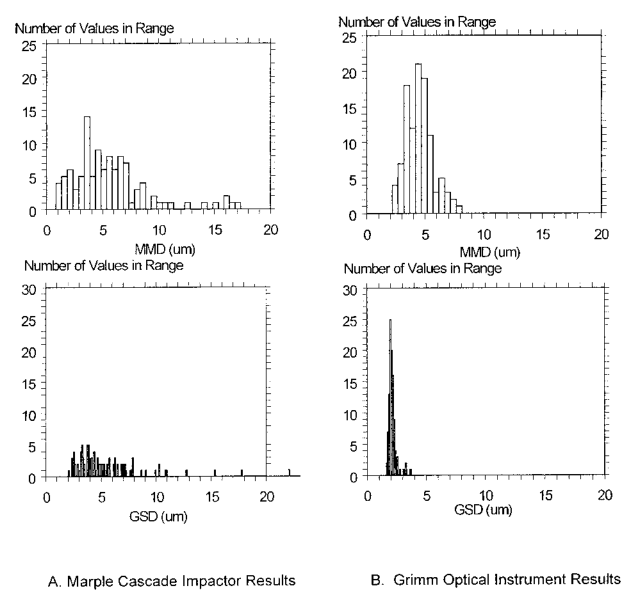

FIGURE 8. Comparison of MMD and GSD results from (A) Marple cascade impactor and (B) Grimm Dust Monitor sampling results

grinding operations (22% versus 8%) and straight oils (53% versus 33%). Both the high exposure and the lower exposure groups had similar frequencies of samples from turning machines (46% versus 42%), which was the most frequently sampled operation in this study. Similar trends were observed for thoracic samples greater than 0.4 mg/m^3.

In a few shops in this study, moderate concentrations of total and extractable particulate were found for "background" samples. Based mainly on their remote placement relative to machining operations, a single sample was collected in each shop that was intended to be representative of the ambient levels of particulate without the contribution of aerosols generated during machining. In most cases the background levels of particulate were much lower than measured in the machining areas. In one shop, however, both the total and extractable concentrations for the background sample exceeded the REL for total particulate. This may indicate that airborne particulate from machining activities in the shop is quite pervasive and suggests the need for better isolation and housekeeping. Alternatively, it is possible that other sources of particulate, present in the areas where background samples were collected, may have contributed significantly to the measured concentrations of extractable particulate. One such potential source is tobacco smoke, which was frequently observed in many of the "background" sampling locations such as office and break areas. A previous study has measured concentrations of tobacco smoke

TABLE VIII. Average Particle Size Distribution Based on Paired Marple Impactor and Grimm Dust Monitor Samples by Operation and Fluid Type

			Marple Impactor		Grimm Dust Monitor	
Operation	MWF Type	N	MMD[A] (μm)	GSD[B]	MMD[A] (μm)	GSD[B]
Boring	synthetic fluid	1	5.3	2.3	3.6	1.8
Milling	soluble fluid	7	5.4	4.7	4.8	2.1
	semisynthetic fluid	7	3.4	6.7	4.4	2.2
	synthetic fluid	1	3.7	22.1	3.0	2.1
Turning						
All	straight oil	40	6.1	5.0	4.5	2.1
	soluble fluid	10	6.0	4.1	4.8	2.2
	semisynthetic fluid	6	3.8	6.7	4.0	2.0
	synthetic fluid	2	2.2	8.1	5.3	3.0
Lathe machine	soluble fluid	9	5.9	4.8	4.8	2.2
	semisynthetic fluid	6	3.8	6.7	4.0	2.0
	synthetic fluid	2	2.2	8.1	5.3	3.0
Screw machine	straight oil	40	6.1	5.0	4.5	2.1
	soluble oil	1	6.7	4.8	4.7	2.2
Broaching	straight oil	1	4.5	2.5	4.8	2.1
Drilling	straight oil	1	3.7	3.8	4.0	2.0
Tapping	soluble fluid	1	16.9	17.8	8.1	2.1
Hobbing	straight oil	3	1.8	5.6	3.0	1.9
Grinding	straight oil	3	10.2	7.9	5.6	1.9
	soluble fluid	4	8.1	4.1	5.0	1.9
	semisynthetic fluid	2	5.8	3.5	4.6	2.1
	synthetic fluid	2	5.7	5.1	4.1	1.9
Overall		105	5.6	5.4	4.5	2.1

[A]Average mass median diameter.
[B]Average geometric standard deviation of the particle size distribution.

exceeding 0.26 mg/m^3 in crowded rooms.[50] Tobacco smoke contains particulate aerosol, which consists of varying amounts of organic compounds such as polycyclic aromatic compounds, which would result in high levels of total particulate as well as extractable matter by the analytical procedure used in this study.[51] A third possibility is that the dust particles in the break area environment act as nucleii for condensation of the vapor-phase contaminants from the shop atmosphere. If the vapor-phase organic contaminants from the shop are ubiquitously distributed in the break area, they conceivably could condense on dust particles, be sampled, and be extracted during the analysis. Such aerosols would contribute to both total and extractable particulate concentrations.

Similar to studies in automotive plants, differences in exposures associated with different types of machining operations and MWFs were found in this study. The highest exposures were found to be associated with grinding and hobbing activities and with straight

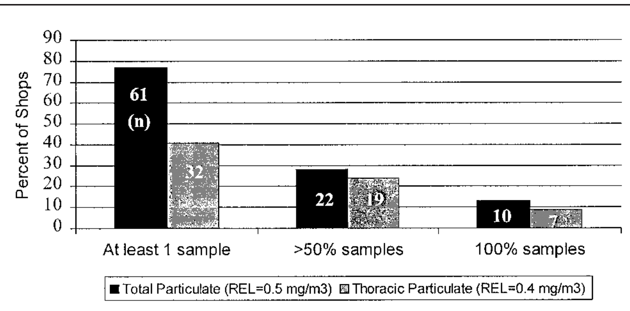

FIGURE 9. Distribution of study facilities with samples greater than NIOSH RELs

or synthetic fluids. It is, however, problematic to differentiate exposures associated with specific machining variables precisely, including process and fluid types, for at least a couple of reasons. First, in most facilities included in this study, there was a variety of machines located in close proximity (i.e., within 10 feet) to each other that were concurrently performing different types of operations and using different parts, metals, fluids, and engineering controls. An example of the close proximity of machines is shown in Figure 10. MWF aerosols generated from a specific machine most likely became mixed quickly with aerosols from surrounding machines resulting in a fairly homogenous MWF aerosol throughout the work area. The moderate level of exposures associated with nonmachining jobs demonstrates the ubiquitous presence of MWF particulate throughout these machine shops. And second, MWF levels in this study are based on personal sampling on a work population that tended to be fairly mobile throughout the shop areas. Most sampled workers were observed to move frequently throughout the shop area while performing duties such as obtaining materials and delivering machined parts. Measured levels are therefore likely the result of exposures to a variety of different MWF emission sources, and consequently to different machining variables.

The MMDs of aerosols measured in this study were generally in the range of 2 to 6 μm. The American Conference of Governmental Industrial Hygienists has developed particle size definitions by curves relating deposition in the respiratory tract to aerodynamic diameter. In simple terms, thoracic particles have an MMD less than 10 μm and may penetrate past the larynx region of the respiratory system. Particles with an MMD smaller than 3.5 μm are considered "respirable" and capable of entering the alveolar region of the lungs.[52] Aerosols measured in the present study

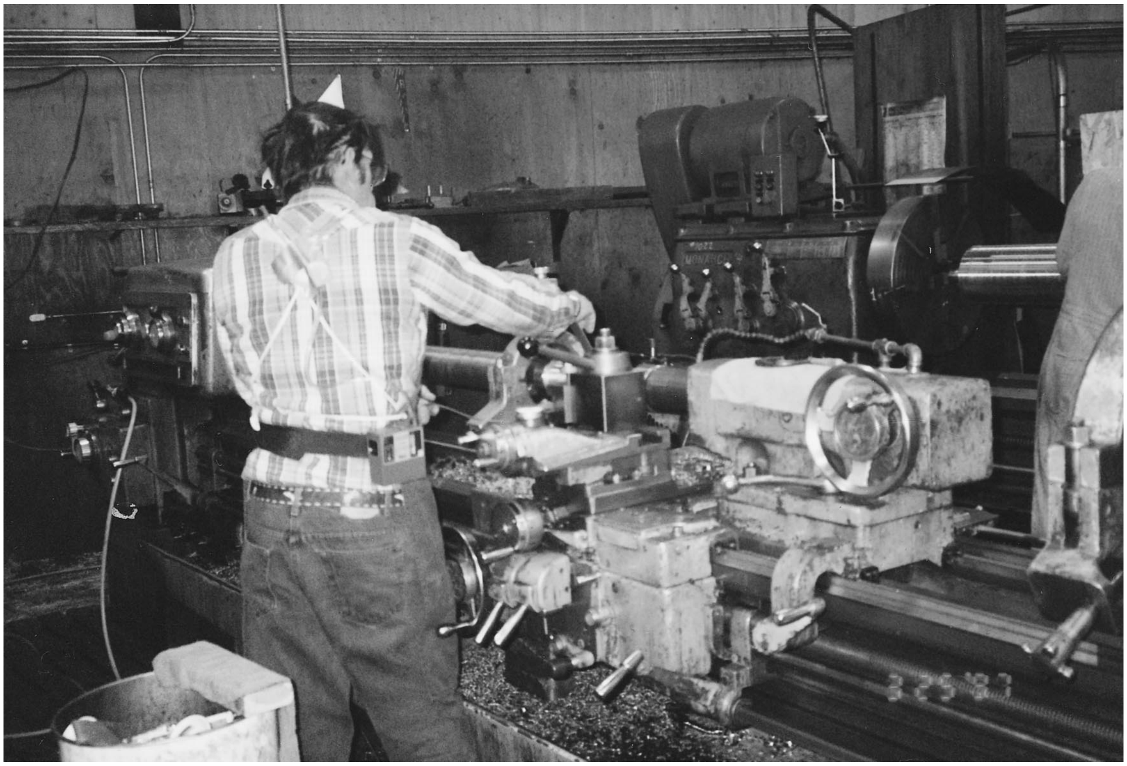

FIGURE 10. Example of the close proximity of machines observed in many study facilities

therefore should be associated with the potential for causing adverse respiratory health effects, such as asthma and impaired lung function, which have been previously demonstrated for MWF aerosols.[2–4, 6,10,16–25]

There were differences in particle size estimates when determined by the Marple impactor versus the Grimm Dust Monitor in this study. The particle size distributions of MWF aerosols measured using the Dust Monitor had an overall mean MMD of 4.5 μm (GSD=2.1). The particle sizes of the aerosols when measured by the impactor were slightly larger and the distributions were much more variable (MMD=5.6 μm; GSD=5.4). There may be several reasons for differences in the particle size distributions as measured by these two samplers. First, the Grimm monitor generally collected an aerosol sample during a 1–5 min interval, whereas the Marple impactor sampled over a 6–8 hour period. These differences in sampling intervals are important if there is significant temporal variation in the particle size distribution of the ambient aerosol, as might be expected in a machining process. The Grimm monitor measurement is representative of the momentary distribution, whereas the impactor samples are more representative of the integrated distribution over the work shift. Second, the particle size estimates from the Grimm Dust Monitor are based on the optical diameter of the sampled particles, whereas the Marple impactor collects particles based on their aerodynamic diameter. This difference results in different sampling and measurement efficiencies between the two samplers, particularly for smaller (<1 μm) and larger (>10 μm) particles. This would affect the estimated MMD and particularly the GSD of the distributions. Finally, the size distribution of an aerosol sample as determined by Grimm Dust Monitor should have higher resolution than the Marple impactor because the particle size measurement is based on more data points (i.e., because the aerosol is "divided" into seven versus two particle size classes). Regardless of method, the largest particles were most often associated with straight oils and soluble fluids. Grinding and turning generally produced the largest particles, whereas hobbing resulted in the smallest particle sizes in this study.

These findings on the particle size of MWF aerosols in small machine shops are generally consistent with those previously measured in the automotive manufacturing industry. In two plants studied by Kennedy et al. using personal impactors, the average MMD was 5.7 μm.[2] Woskie et al. found mean MMDs ranging from 3.8 to 8.2 μm across machining operations in three automotive parts manufacturing facilities.[8] In another study, Woskie et al. reported a smaller mean particle size (MMD=3.4 μm) based on 40 area impactor samples collected at an automotive plant described as a "very large specialty job shop."[10] Both of the studies by Woskie found GSDs for particle size distributions that were generally between 2.5 and 3.5—considerably lower than found in this study when using the same sampling method (i.e., Marple personal impactors). The differences in particle size distributions reported from the Woskie studies compared with this study may be due to several factors. For instance, values for the MMD and GSD in the Woskie study were estimated visually from log probability plots, whereas these values were determined by linear regression techniques in this study. Also, any differences in the weighing procedures, such as using balances with different analytical sensitivities, may possibly account for differences in results between these studies. Finally, the much lower variability reported by Woskie may be explained by the fact that all of the particle size samples in her studies were collected in only four plants within a single industry (automotive parts manufacturing). Particle size distributions in this study were collected from 79 shops over 32 different industries and are therefore likely to be inherently more variable.

The mean ratio of thoracic to total particulate concentration in this study was found to be 0.55. This means that a total particulate measurement should be divided by 1.82 to calculate an equivalent thoracic concentration. NIOSH has recommended a correction factor of 1.25 based on data from Woskie.[8,38] This difference is likely due to the smaller particle sizes (and therefore higher thoracic fractions) generally measured by Woskie in the automotive plants compared with the present study and their use of a different sampling method for estimating both thoracic and total particulate (i.e., Marple impactor). Davies et al. reported estimates of thoracic particulate (using the PEM monitor) that were 1.6 times that of the 37-mm total dust sampler in the woodworking industry.[53] The authors advised that developing "intersampler ratios" comparing total dust sampler measurements with particle size selective measurements is problematic because the intersampler ratio is dependent on the underlying particle size distribution and the qualitative homogeneity of the particulate. This suggests that the correction factor for determining equivalent thoracic particulate concentration, or vice versa, should be based minimally on industry type, and ideally be experimentally measured in the specific environment of interest. This is consistent with previous recommendations by NIOSH.[38]

It should be mentioned that subsequent penetration measurements of the thoracic sampler used in this study (the GK2.69 cyclone) indicated that a sampling flow rate of 1.6 L/min (rather than 1.8 L/min) resulted in the closest agreement with the thoracic convention.[54] The effect of sampling at the higher flow rate would be dependent on the underlying particle size distribution of the aerosol. The extreme case would involve an aerosol with a large MMD where the thoracic fraction is small (i.e., <10% of the total); the thoracic concentration is this case would be underestimated by about 15%. More likely, the thoracic concentrations measured in this study are only slightly underestimated (<5%), based on measurements of the MWF size distributions in these shops. The error due to the higher flow rate therefore is considered negligible and does not change any of the conclusions from this study.

Previous studies have found that the use of engineering controls on machining equipment generally has resulted in lower exposures to MWFs.[55–57] For instance, Hands et al. reported that automotive plant employees operating equipment with OEM total enclosures and exhaust ventilation had significantly lower exposures to MWFs than employees operating equipment with partial or retrofit enclosures or equipment with no enclosures.[55] Interestingly, in the present study lower mean exposures were associated with machines without any engineering control compared with machines with either full or partial enclosures or splash guards. These differences in exposures for different engineering controls were not statistically significant, probably because of the "homogeneity" of aerosols in these relatively small work environments (i.e., it was difficult to differentiate exposures associated with many machining variables because of the close proximity of machines operating under different conditions). Nevertheless, this trend of higher exposures for machines with engineering controls is still unexpected. One possible explanation is that engineering controls were more often used on those machines most likely to generate the highest MWF emissions, as was reported by shop owners. For example, it is reasonable to assume that, in the absence of engineering controls, higher machining speeds inherently generate higher emissions than lower speeds. Empirically, mist generation has been shown to increase as the square of the tool speed.[56] In this study the average tool speed of machines with full enclosures was about 2100 rpm compared with 800 rpm for machines without any engineering control. Therefore, although an engineering control may, in fact, reduce emissions for a given "high-speed" machine, the resultant exposure may still be comparatively higher than for a "slower" machine without any control.

Because of the cross-sectional nature of the survey data within and between shops, it is difficult to differentiate the relative effectiveness of different types of controls. For instance, in many shops a machine with no enclosure would be immediately adjacent to a machine with a full enclosure, so it was difficult to measure the associated exposures separately. Ideally, to evaluate the relative effectiveness of a control method, exposure measurements should be taken on the same machine both with and without a given control in the absence of other confounding sources of aerosol. This was not possible in this study. However, other studies have shown that a comprehensive control strategy can reduce MWF emissions effectively. Yacher et al. demonstrated that ventilating a fully enclosed machining center, enclosing the flume, and enclosing and ventilating the MWF sump reduced the total particulate levels from 0.22 to 0.06 mg/m³.[57] Further studies are needed to assess the effectiveness of similar engineering controls properly for reducing MWF exposures in small machine shops.

SUMMARY

Most exposures to MWF mists in this study of 79 small machine shops were below limits established by NIOSH and recently recommended by an OSHA MWF advisory committee. More than 60% of samples were below the recommended exposure limit of 0.5 mg/m³ for total particulate and almost 80% were below the REL of 0.4 mg/m³ for thoracic particulate. However, in some shops many, if not all, of the measured exposures were above these exposure guidelines. Also, some machining situations, such as using straight oils or performing grinding or turning operations, were consistently associated with higher exposure levels. Measured exposures are of health significance because the MMD of aerosols in this study were generally between 2 to 6 μm and therefore capable of thoracic and respiratory deposition. Both the levels and the particle sizes of MWF aerosols in small machine shops were found to be similar to those previously reported in large automotive plants. These findings suggest that there may be similar risks for increased health effects, such as respiratory illnesses and dermatitis, which have been previously observed among MWF-exposed workers in the automotive industry.

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