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Metalworking Fluid Mist Occupational Exposure Limits: A Discussion of Alternative Methods

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NIOSH published a recommended exposure limit (REL) for metalworking fluids (MWF) in 1998 that was designed to prevent respiratory disorders associated with these industrial lubricants. The REL of 0.4 mg/m^3 (as a time-weighted average for up to 10 hours) was for the fraction of aerosol corresponding to deposition in the thoracic region of the lungs. This nonregulatory occupational exposure limit (OEL) corresponded to approximately 0.5 mg/m^3 for total particulate mass. Although this REL was designed to prevent respiratory disorders from MWF exposures, NIOSH acknowledged that exposures below the REL may still result in occupational asthma and hypersensitivity pneumonitis—two of the most significant respiratory illnesses associated with MWF. In the 8 years since the publication of the NIOSH MWF REL, neither the Occupational Safety and Health Administration (OSHA) nor the American Conference of Governmental Industrial Hygienists (ACGIH®) has recommended an exposure limit for water-soluble MWF specifically, other than their previous exposure limits for mineral oil. An informal effort to benchmark companies involved in the manufacture of automobiles and automotive parts in North America indicated that most companies are using the NIOSH MWF REL as a guide for the purchase of new equipment. Furthermore, most companies have adopted a goal to limit exposures to below 1.0 mg/m^3. We failed to find any company that has strictly enforced an OEL of 1.0 mg/m^3 through the use of either administrative controls or personal protective equipment, when engineering controls failed to bring the exposures to below this limit. We also found that most companies have failed to implement specific medical surveillance programs for those employees exposed to MWF mist above 1.0 mg/m^3. Organization Resources Counselors (ORC) published in 1999 (on their website) a "best practices" manual for maintaining MWF systems and reducing the likelihood of MWF-related illnesses. The emphasis of this approach was on control techniques, and there was no assignment of a specific OEL for MWF due to the wide variety of fluids that exist. The ORC did suggest that maintaining exposure levels to below 2.0 mg/m^3 would assist in minimizing upper respiratory complaints associated with MWF. Although the ORC manual indicated that MWF vary in composition and no single OEL is likely to be appropriate for all such fluids, it adopted a very similar concept to control banding, placing all MWF operations into a single band using similar (if not identical) controls. OSHA, in lieu of adopting a 6B health standard for MWF, has also published a voluntary "best practices" manual on their website. Their document drew heavily from the work of ORC and also incorporated information from the 1998 NIOSH MWF criteria document. Industrial users of MWF need to have guidance, such as an OEL, to determine when either engineering, administrative controls, or personal protective equipment must be implemented to protect their employees. The purpose of this article is to explore various approaches that might be taken to result in a single or multiple limits for exposures to MWF and its components. Approaches such as control banding are discussed in terms of an alternative to the use of an OEL.

Keywords control banding, exposure assessment, metalworking fluids, mist generation, occupational exposure limits, risk assessment

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INTRODUCTION

During the early development of metalworking technologies, mineral and animal oils were used extensively as industrial lubricants to reduce friction at tool-workpiece interfaces. Studies in the early 1900s clearly demonstrated the utility of using water to cool frictional surfaces and, thus, extend tool life.[1,2] The term "coolant" is frequently used today to describe water-soluble metalworking fluids (MWFs). The first water-soluble cutting fluid was developed in 1945.[3] A comprehensive treatment of MWF history is provided in Byers et al.[4]

Metalworking fluids are complex chemical mixtures that can be grouped into four major categories:

1. *Straight oils.* Mineral (most common), vegetable, animal, marine oils with no water content; petroleum-based oils may be severely hydrotreated or severely solvent refined to reduce polynuclear aromatic hydrocarbon content
2. *Soluble oils.* 30–85% naphthenic or paraffinic oil containing emulsifiers and additives

3. *Semisynthetic fluids*. 5–20% mineral oil emulsified in water
4. *Synthetic fluids*. No mineral oil content; a mixture of organics and additives to provide lubricity (reduce friction) and corrosion prevention, 70–95% water content.

Routinely, MWF products are provided to end-users as concentrates that are then diluted with water from 1–20% at the point-of-use. In this regard, an average dilution of about 5% is commonly used for many machining applications.

Manufacturers of MWF have modified formulations over the years in response to health and environmental concerns. Examples of these modifications:

- Removal of *nitrites* (rust inhibitors)—potential to combine with secondary amines to form carcinogenic nitrosoamines
- Removal of *polychlorinated biphenyls* (high-pressure lubricants)—toxicity, mutagenicity concerns
- Reduction in use of *diethanolamines* (corrosion inhibitors)—toxicity concerns
- Reduction of *phenolic compounds* (biocides) — recalcitrant to wastewater treatment
- Removal of *4-tert-Butylbenzoic acid* (corrosion inhibitor)—potential allergen
- Removal of *dichromates* (corrosion inhibitors)—potential allergens, cause skin disorders
- Severe refining of mineral oils (lubricants) to reduce *polynuclear aromatic* content—potential tumorigens, adverse reproductive effects
- Replacement of *glycol ethers* (couplers)—may form explosive peroxides
- Reduction in use of *barium sulfates* (emulsifiers)—insoluble and resistant to wastewater treatment.

Various chemical additives are formulated into metalworking fluids in order to achieve specific performance requirements. Categories of common additives and their basic functions are shown in Table I. Additive "packages," that is, combinations of chemical additives, may be introduced into MWF formulations to fulfill specific machining requirements, such as lubricity specifications, corrosion resistance, biocidal effectiveness, high-speed/high-pressure applications, and so on.

Diluted MWF contained in both small sumps and large central systems are prone to microbial contamination by various species of bacteria, fungi, and algae. Metalworkers may be exposed to MWF aerosols of mixed compositions that contain intact microbial cells, cell fragments, and metabolites, in addition to organic and inorganic compounds found in fluids, and contaminants that enter fluids during routine operations.

TABLE I. Examples of MWF Additives

Additive Type	Examples
Corrosion inhibitors	Amine carboxylates, amine borates, tolytriazole salts
Emulsifiers	Soaps, sulfonates, alkanolamides
Couplers	Glycol ethers
Extreme pressure (EP) lubricants	Sulfurized, phosphated compounds
EPA-approved Biocides	Triazines, oxazolidines, isothiazolones, phenolics
Lubricants	Sulfurized fatty oils, phosphate esters, dibasic acid esters
pH buffering	Alkanolamines
Dispersants	Primary amino alcohols

METALWORKING FLUID USAGE

An estimate of metalworking fluid production in the United States by the Independent Lubricant Manufacturers Association (ILMA) states that 95–103 million gallons of MWF were produced annually between 1994 and 1999.[5] Of the 284 companies listed in an industrial lubricants trade publication,[6] fewer than 10 produce approximately 25% of the current total U.S. MWF production. Production volumes of all categories of MWF closely track market demands of industrial users that use high volumes of MWF, such as automotive, agricultural, commercial aircraft, and heavy machinery industries.

Methods of applying fluids in machining processes have essentially changed very little over the years. Fluids are still copiously flooded or sprayed over workpiece-tool interfaces to accomplish a number of functions:

- Provide lubricity to cool the tool-workpiece interface (cutting zone)
- Reduce extensive tool wear
- Flush metal swarfs and fines (chips) from the cutting zone that obscure worker vision
- Prevent potential welding of swarfs and chips to tool and workpiece surfaces
- Facilitate formation of desirable surface finishes on metal parts.

Minimal quantity lubrication (MQL) and dry machining methods have been suggested as alternatives to conventional MWF modalities.[7] However, MQL and dry machining techniques are not widely utilized in most machining industries.

METALWORKING FLUID AEROSOL (MIST) GENERATION AND EXPOSURES

Dynamic forces exerted on MWF during machining operations, for example, impaction, centrifugation, and high-pressure spraying (fluid atomization), produce polydisperse aerosols as a result of the violent and rapid fracturing of fluid streams. Also, aerosol generation may be influenced by the composition of fluids and their contaminants.[8] The settling rate of individual MWF aerosol particles varies with their density and volume and, consequently, larger particles settle at a faster rate than smaller particles.[9] Metalworking fluid aerosols produced in a given area may have relatively extended residence times in the air (buoyancy effects) to form a mist or bluish haze that is readily visible to the unaided eye. The reduction of MWF mist concentrations in work areas is largely dependent on the effectiveness of engineering controls, especially general and local ventilation, and good fluid management.

Metalworking fluid aerosols within the respirable range (i.e., $< 5\ \mu$m aerodynamic equivalent diameter) are of primary importance to industrial hygienists because these particles can penetrate to the lower regions of the lungs. Larger particles may lodge in the nasopharynx and contribute to upper respiratory system irritation and throat and eye irritation, and foster complaints of nuisance odors.

According to a National Occupational Exposure Survey (NOES) conducted by the National Institute for Occupational Safety and Health (NIOSH), it is estimated that 1.2 million workers are potentially exposed to metalworking fluids.(10) It is difficult to assess an average diurnal exposure because workers frequently perform different tasks during any given work shift, and exposure conditions within machining facilities fluctuate on a continuous basis.

THE INHALATION HAZARDS OF METALWORKING

The hazards of any substance can be generally thought of as a product of its inherent toxicity and the exposure or dose that a worker receives. More subtle issues may enhance the hazard, such as individual susceptibility to a specific agent or illness. The most common complaint or illness associated with MWF is dermatitis. Respiratory effects fall into three main categories: upper respiratory irritation, asthma, and hypersensitivity pneumonitis (HP), which is an immunologically mediated pulmonary disease and the most serious of these. The chronic form of HP can result in long-term debilitation or death.

The inhalation hazards of MWF are caused by exposure to three agents: the neat or diluted MWF, microbial contaminants, and other chemical contaminants of the fluids. The neat fluid comprises chemical agents, some of which have existing OELs, such as mineral oil, ethanolamine, and diethanolamine. Other additives used for corrosion inhibition, antimisting, and biocides do not have existing OELs. Obviously, those components that have existing OELs can be monitored and assessed for their hazard.

Another approach is to consider that these chemical components produce an acute hazard in the form of respiratory irritation. Krystofiak et al.(11) have studied neat MWF and associated components in a mouse bioassay designed to determine the respiratory irritation of chemicals. The authors recommended an OEL of 2 mg/m^3 based on testing the components of MWF along with the entire fluid. This value is similar in magnitude to existing OELs for mineral oil, mono- and diethanolamine, which are 5–6 mg/m^3.

Biological agents generally do not have established OELs. Well-known and extensively studied agents such as *Mycobacterium tuberculosis* do not have OELs. The reasons for this are the difficulty in quantitatively assessing exposures as well as the variability in responses among humans. Two biological agents deserve special attention when assessing the hazards of exposure to in-use metalworking fluids. (1) Endotoxins produced by gram-negative bacteria (GNB). Endotoxin (the outer lipopolysaccharide moiety of the outer cell membrane of GNB bacteria) has been implicated in causing asthmatic responses in some individuals. Heederik(12) has suggested that endotoxin levels in air be kept below 45–50 EU (endotoxin unit)/m^3, a value that corresponds to approximately 5 ng/m^3. The Dutch government has established an OEL of 4.5 ng/m^3 for endotoxin.(13) A second important group is (2) *Mycobacterium* sp. that have been suggested as responsible agents for outbreaks of HP.(14) In one published study,(15) the authors suggest an association between a single bacterial species in MWF, *Mycobacterium immunogenum*, with HP. However, this hypothesis is tenuous because a correlation between MWF exposure and HP is not always consistent. No one has suggested an OEL for any *Mycobacterium* sp., but outbreaks of HP have been associated with 50–2250 CFU/m^3 in air, with up to 6.6×10^6 CFU/mL in contaminated fluid.(16)

A related hazard associated from microbial contamination of MWF is from the chemicals that arise from the metabolites of these organisms. Some anaerobic bacteria, for example, *Desulfovibrio desulfuricans*, produce sulfur compounds that are both objectionable and irritating to workers.

There are other contaminants that accumulate in active MWF distribution systems. The most notable are tramp oils that arise from leaks in machinery and migrate into the MWF. Tramp oils have been suggested as causative agents that augment the misting potential of MWFs and, consequently, increase airborne exposures to workers.(8) Tramp oils can also lead to a faster biodegradation of the MWF system. Tramp oils are chemically similar and probably have an inherent toxicity comparable to mineral oil in terms of respiratory irritation.

RISK ASSESSMENT APPROACHES TO MWF

Occupational Exposure Limits

There are several approaches that have been used in both the risk assessment and control of occupational health hazards. The most widely accepted and traditional method for risk assessment used for chemical contaminants in the workplace is to establish OELs. These values can be based on animal toxicity data, human toxicity data for some acute hazards (mostly upper respiratory irritants), epidemiologic data for chronic hazards, or a combination of these data.

The only OEL currently established for MWF has been by NIOSH.(17) Their standard of 0.4 mg/m^3 of thoracic particulate mass is "intended to prevent the diverse respiratory effects associated with MWF exposure."(17,p.171) The agency goes on to state that "some workers have developed work-related asthma, hypersensitivity pneumonitis (HP), or other adverse respiratory effects when exposed to MWF at lower concentrations."(17,p.1) The NIOSH recommended exposure limit (REL) is the same for all four types of MWF, a recognition that there are not significant differences in risk among the various fluid types.

The Occupational Safety and Health Administration (OSHA) has a permissible exposure limit (PEL) of 5.0 mg/m^3 for mineral oil mists,[18] and the American Conference of Governmental and Industrial Hygienists (ACGIH®) has a consensus threshold limit value (TLV®) of 0.2 mg/m^3 in its "2005 Notice of Intended Change" for mineral oil with carcinogenicity designations: "Poorly and mildly refined" (A2-Suspected Human Carcinogen), and "Highly and severely refined" (A4-Not Classifiable as a Human Carcinogen).[19] In 2005, ACGIH removed MWF from its "Under Study List."

When examining the NIOSH criteria document used to communicate the REL for MWF, the agency did not use a quantitative risk assessment in their approach. The document does not identify what the agency considered as a no observed adverse effect level (NOAEL) nor what safety factor they assigned to this value, a traditional approach in establishing an OEL. Furthermore, NIOSH described a variety of adverse health effects: asthma, upper respiratory irritation, cancer, and other effects without identifying which of these effects are the most sensitive (caused by the lowest concentration of MWF) and should be the basis for an OEL. In its criteria document under "Basis for the Recommended Standard," NIOSH stated that an examination of the OSHA IMIS database indicated that between 1991–1995, 73% of the air samples for MWF were below 0.5 mg/m^3.[17] This suggests that the agency's approach was not based on a quantitative risk assessment, but used "As Low As Reasonably Achievable" (ALARA), an approach that has been used for substances where no safe threshold for an exposure is known (e.g., ionizing radiation).[20]

Some organizations have suggested that a single OEL for MWF is not feasible because the neat fluids vary from manufacturer and subsequent exposure to used fluids that become contaminated with both microbial agents and other unwanted substances (e.g., tramp oil) make MWF too heterogeneous to assign a single OEL. Organization Resources Counselors (ORC, a coalition of large employers) in its published management guide to MWF declined to provide a specific OEL for MWF and stated "... since the relationship between exposure and adverse health effects is not well understood, a specific exposure limit cannot be established to ensure the health of the workforce (ORC, 1999)."[21] They then stated that levels above 2 mg/m^3 are likely to lead to respiratory irritation and should be immediately addressed, whereas levels between 1–2 mg/m^3 may also result in complaints and should be lowered. ORC recommended a target level below 1 mg/m^3 for MWF.

We contacted health and safety professionals at six large (e.g., >1000 employees) corporations involved in automotive production or automotive parts manufacturing to understand how they approach the protection of employees exposed to MWF. Our discussions found that these organizations use the NIOSH REL value as the basis for designing new MWF systems, and a value of 1.0 mg/m^3 for existing in-place processes. We were informed that some union contracts have specified such language to protect the health and safety of their members. Our understanding is that these employers and their unions use the NIOSH REL as an engineering control target and not an OEL. We failed to find any of these companies that routinely used administrative controls (e.g., job rotation) or respiratory protection to address those exposures that exceed 1.0 mg/m^3.

Best Available Control Technology and ALARA

EPA in its early years used the term "best available control technology" (BACT) in approving pollution control systems.[22] The approach was mandated under the Clean Air Act for new processes. This approach fails to assign a risk level to a certain contaminant(s), but rather requires manufacturers to implement the best control technology that exists. EPA defines BACT as: "The application of the most advanced methods, systems, and techniques for eliminating or minimizing discharges and emissions on a case-by-case basis as determined by EPA. The determination of BACT takes into account energy, environmental, economic effects, and other costs." The agency continues to keep a current database of various methods to control pollution.[23]

A similar approach is to limit hazards to "as low as reasonably achievable" (ALARA). The underlying concept is that there is no threshold for an effect, so that with each increase in exposure there is a concurrent increase in risk to a worker. The best known examples of such substances are those that produce ionizing radiation. The Department of Energy (DOE) has stated: "It is DOE's policy that radiation exposures resulting from its operations are maintained within regulatory and administrative limits, and further that such exposures are as low as reasonably achievable. Reducing radiation exposures to levels that are ALARA has long been the goal of the radiological safety programs at the DOE and its predecessor agencies."[24] However, even with ionizing radiation, EPA provides a level for radon gas of less than or equal to 4 pCi/L in air for homeowners in which they determine remediation is not required. More recently, EPA has provided a quantitative risk assessment for radon gas exposures in homes that corresponds to 23 lung cancer deaths per 1000 in the general population (7.3 per 1000 for nonsmokers) for exposures at their action level of 4 pCi/L.[20]

ORC and OSHA Best Practices Guidelines for MWF Operations

ORC and OSHA both issued guidelines in the late 1990s to assist companies that used MWF.[17,21] The approach was similar to BACT only in a nonregulatory manner. Each organization produced documents that are based on a variety of information that was known to limit exposures to MWF and control microbial contamination. The ORC document included management and control items, such as MWF selection, maintenance, enclosures, ventilation, and mist collectors. ORC recommended that bacteria levels in MWF be kept to below

10^3–10^5 CFU/mL and that fungi levels be kept to below 100 cells/mL.

The OSHA document *Metalworking Fluids: Safety and Health Best Practices Manual* contains a compilation of information from the ORC document and NIOSH criteria document.[25] Unlike the ORC document, OSHA's manual fails to suggest specific levels for microorganisms in the fluid or air nor does it recommend a specific guideline for MWF exposures in air.

Control Banding

Control banding has been used by the pharmaceutical industry in the United States since the mid-1990s[26] and by the U.K. Health and Safety Executive ("Control of Substances Hazardous to Health Regulations," i.e., COSHH essentials).[27] The concept is to put chemicals (and other substances and processes) into one of a number of "bands" depending on its hazard. The hazard is a combination of the inherent toxicity of the substance and the likely exposure. The exposure is assessed qualitatively by determining the form in which the chemical exists (particle size, gas, vapor), the quantity used, and the processes in which it is used. The approach recommends control strategies to be chosen prior to and possibly in lieu of exposure measurements taken in the workplace.

Control banding may be useful in situations where there are no OELs and/or when quantitative exposure assessments would be difficult to obtain (e.g., small industries that lack the technical expertise or in developing nations). The pharmaceutical industry has used this approach to establish engineering controls for new chemicals and products it processes. Generally, each control band represents a hazard approximately 10 times lower than the band above and 10 times higher than the band below. This approach appears to be well suited for pharmaceutical facilities where many controls have been standardized and where various companies have collaborated to validate the recommended controls with quantitative exposure assessments.

The use of control banding has been considered for industries using MWF in lieu of the development of an OEL. However, there are some distinct differences that would make this approach less useful than in other manufacturing environments, such as the pharmaceutical industry. First, MWF, unlike chemicals used in the pharmaceutical industry, all have approximately the same inherent toxicity to begin with. NIOSH and ORC have advocated using a single OEL (or a range of values) for all four major types of MWF. Furthermore, irritation studies conducted in animal models have suggested that neat fluids do not significantly differ in their irritation potential. Therefore, all MWF users and operations would have a single control band. In fact, this is the approach suggested by ORC and OSHA in developing their recommendations for managing MWF systems.

Control banding requires validation of the effectiveness of the implemented controls. Validation would require the ability to measure airborne MWF levels (or their constituents) and compare them to a specific OEL. Other methods of validation could include the measurement of microbial contamination in the fluid itself (and comparison to a standard) and medical surveillance of the work force. A combination of all three approaches would make the most sense. It certainly could be argued that once effective controls are in place and validated, the need for routine exposure assessments would be less important.

EXPOSURE ASSESSMENT FOR METALWORKING

Metalworking fluid exposures in air have generally been assessed using one of three methods: integrated monitoring for total particulates, integrated monitoring for MWF specific components, and direct-reading monitoring for either total aerosols or size-selective fractions of the aerosols.

There are two major questions to consider when establishing a method for monitoring metalworking fluid: What size aerosol are you interested in collecting and what in the aerosol do you want to analyze for? NIOSH has recommended measurement of the thoracic particulate fraction of aerosols. This would collect aerosols responsible for both asthmatic responses and deep lung irritation in workers. However, this fraction would exclude larger aerosols that might cause upper respiratory irritation in the nose and throat of workers.

The OSHA method (ID-128) for mineral oil collects total particulates and then the fraction that is soluble in carbon tetrachloride is analyzed and compared by infrared spectrophotometry to the base mineral oil for quantification.[28] A proposed ASTM method for oil mist has a similar approach but uses a combination of three solvents and a simple gravimetric analysis.[29] The mass of the fraction that is soluble in the solvent is subtracted from the mass of the total aerosol that was collected to obtain the mass of metalworking fluid collected. NIOSH also has a method that uses a solvent extraction of a filter and infrared analysis to quantify mineral oil.[30] All of these methods make the basic assumption that the fraction of aerosols not soluble in a solvent is not important from an occupational health perspective. This fraction would include water-carrying bioaerosols.

Whatever method of MWF collection chosen, it would be directly linked to an OEL. This has been demonstrated with changes to threshold limit values (TLVs) for certain aerosols. The TLV committee has changed the designation (and method of collection) of some aerosols from total dust using a closed-faced cassette to an inhalable fraction. In doing this, the actual TLV value was not changed but only the designation of the aerosol fraction to be collected. The result of side-by-side measurements have often found substantially higher levels of aerosols collected with an inhalable sampler than with a closed-faced filter cassette. Hence, some workers who had exposures below the TLV now have exposures above this standard with no changes to the process and no quantitative changes to the TLV value.[31]

AN INTEGRATED APPROACH TO MWF

The establishment of an OEL (e.g., the NIOSH REL) for MWF would be an effective approach for minimizing and evaluating the upper respiratory irritation that may be caused by neat or diluted neat MWF. However, such an OEL would fail to address the hazards (e.g., asthma and HP) caused by microbial contaminants. In a similar manner, an MWF management control advocated by ORC and OSHA is a useful approach for designing and maintaining MWF systems but not for evaluating exposures of workers in these environments. We propose an integration of these approaches for the management and control of MWF and for the identification of exposures that must be addressed with engineering, administrative, or personal protective equipment. These approaches are briefly described as follows and recommendations are summarized in Table II.

MANAGEMENT OF MWF SYSTEMS

We favor approaches identified by ORC and OSHA in their respective documents for controlling MWF exposures. These include but are not limited to:

- proper selection of MWF and their additives
- maintenance of fluids to minimize the growth of microbial contaminants
- minimizing and controlling the unnecessary contamination of fluids with other substances, such as tramp oils
- machine enclosures and mist collectors to minimize the generation of MWF aerosols in the workplace environment
- the use of cycle times and other administrative controls to avoid unnecessary generation of aerosols in the workplace.

ESTABLISHMENT AND COMPLIANCE WITH AN OEL FOR MWF

We recommend, as does NIOSH, a single OEL for all types of MWF. The OEL is based on the effects of the neat and diluted MWF and may not provide protection against certain pathogenic organisms (e.g., *Mycobacterium* sp.) that can develop in the MWF. Animal and human data indicate that 2 mg/m^3 will produce upper respiratory irritation, and a level of 1 mg/m^3 will be protective for many workers. Given that many workplaces can already meet a 0.5 mg/m^3 standard, this should be a target level when designing or redesigning existing equipment.

Where exposures exceed 2 mg/m^3 (as an 8-hr TWA), we recommend administrative controls (e.g., job rotation) and/or the provision of respiratory protection to reduce exposures until proper engineering controls are instituted. A minimum level of respiratory protection would consist of a NIOSH-approved, air-purifying, half-facepiece respirator with P or R filters. The use of respirators should be only a temporary measure until suitable engineering controls are instituted. Employees exposed to MWF at levels below 2 mg/m^3 should be offered the opportunity to wear a respirator should they request one.

We recommend air sampling for total particulates as opposed to only the "thoracic fraction" that is recommended in the NIOSH criteria document. The rationale for this is that aerosols larger than those collected using a thoracic sampler may contribute to upper respiratory irritation. The proposed ASTM PS42-97 method for analysis of MWF will provide more reproducible results than using a simple gravimetric analysis, due to variability caused by the evaporation of water.[30] Given that the OEL is based on the effects of MWF and their additives and not from microbial contaminants carried by water, we would recommend this method for analysis.

MEDICAL SURVEILLANCE OF WORKERS EXPOSED TO MWF

We recommend that a medical surveillance program be established by a qualified licensed health care professional and implemented for all workers routinely exposed to MWF. Because of the potential for microbial contamination of MWF, exposures below an OEL may not protect workers against some of the most serious complaints and illnesses associated with MWF exposures. Minimally, employees should be asked to complete a questionnaire that identifies respiratory illnesses. Examples of questionnaires may be found on the American Thoracic Society website.[32] Ideally, workers

TABLE II. Summary of an Integrated Approach to Control MWF Exposures

	Engineering Controls	Administrative Controls	Respiratory Protection	Medical Surveillance
Exposure (mg/m^3)				
< 0.5	O	—	O	S
>0.5–1.0	S	—	O	S
1.0–2.0	R	O	O	S
>2.0	R	R	R	R

Notes: When exposures exceed 2 mg/m^3, engineering controls, administrative controls, and respiratory protection are not all required, but the combination of these are required to control exposures and protect workers. O is optional, S is strongly suggested, and R is required.

would also have annual pulmonary function testing to evaluate changes in the breathing pattern and capacity. If the data collected were evaluated by occupational health experts at each facility, or better by an industry coalition in the future, one could better estimate an OEL that was protective for workers.

FUTURE RESEARCH NEEDS

The following is a limited list of issues that we identified in writing this article that need to be better understood:

- What organisms are responsible for causing HP, and what types of controls are necessary to avoid these outbreaks in facilities that use MWF?
- What size-selective fraction of aerosols is most important to collect when providing exposure assessments of MWF?
- A laboratory method for analysis of MWF integrated air samples needs to be finalized and recognized as a standard method.
- What long-term respiratory effects are identified with workers exposed to MWF at or above 1.0 mg/m^3 and those with exposures below 0.5 mg/m^3?

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